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Exploratory Workshop on the

Social Impacts of Robotics

Summary and Issues

A Background Paper

OTA Background Papers are documents that contain information believed to be useful to various parties. The information undergirds formal OTA assessments or is an outcome of internal exploratory planning and evaluation. The material is usually not of immediate policy interest such as is contained in an OTA Report or Technical Memorandum, nor does it present options for Congress to consider.

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Preface

Advanced computer and communication technology is providing a wide assortment of new tools for improving industrial productivity by automating manufacturing. Robotics technology is an important component of modern automation technology, one in which U.S. industry is vitally interested.

On July 31, 1981, the Office of Technology Assessment held an exploratory workshop to examine the state of robotics technology and possible public policy issues of interest to Congress that may arise from its use. The workshop participants included researchers in robotics technology, representatives from robot manufacturing firms, and representatives from firms that use robotics technology. The principal goals of the workshop were the following:

- assess the state of robotics technology;
- examine the structure of the robotics market;
- determine the relationship of robotics to other new automation technology; and
- determine whether significant Federal policy issues were likely to be raised.

This report contains a summary of the results of the workshop along with copies of four background papers that were used as starting points for the discussion. The workshop was exploratory in nature, and OTA does not at this point take any position on the merits of the issues discussed or on their worthiness for future assessment.

John H. Gibbons

JOHN H. GIBBONS
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*On detail from the Department of Commerce.

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I.

Introduction

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I.

Introduction

Background

The topic of industrial robots has recently been given increased attention. Articles in the technical and popular press have discussed the potential of robots to boost U.S. industrial productivity and enhance international competitiveness (1,2). Others have concentrated on the effects of robots on employment and their potential to change the workplace environment and alter the nature of work (3,4).

This same interest in robotics technology has been expressed informally to OTA by congressional staff from several committees. Other OTA studies in such areas as information policy, educational technology, innovation, and industrial competitiveness have touched on the impacts of robotics technology in light of those issues.

To date, a primary thrust of domestic U.S. interest in robotics seems to be the belief that robots, along with other new automation technology will be an important tool for improving the competitiveness of U.S. manufacturing. The use of robots may lower production costs, improve the quality of manufactured goods, and reduce workplace hazards. A clear theme has been the concern that foreign competitors may be gaining a significant edge over the United States both in using this new production technology and in establishing a competitive position in the potentially major export market for robots.

Some writers have also expressed concern about possible impacts of this technology on workers as it becomes more widely used. They have stressed possible unemployment, the need for new and different skills, and effects on the work environment.

Abroad, interest in robotics has been intense. England, Japan, Germany, Norway, Italy, and Sweden have initiated government and private efforts to develop robotics technology and stimulate its use in manufacturing. Some of these countries have also undertaken studies to assess ways in which automation may create or eliminate jobs.

In response to congressional interest in public policy issues related to robotics, the rapid advances in computer technology and its applications, and public concern about the state of the U.S. industrial economy, OTA sponsored an exploratory workshop to discuss the future of industrial robotics and its likely impact on public policy. The purpose of this paper is to summarize the results of this effort and to make available several informal papers prepared for that workshop. Most of the information is based on discussions at the workshop, commissioned papers,* and other material collected prior to the workshop.

The summary presents background information and identifies key questions and issues that were raised to the OTA staff during the course of the project. It does not contain analysis or evaluation of these issues. It also does not present any options for Federal policy or analysis of such options.

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*Attached to this report as app. B.

Workshop Goals

The workshop had several goals:

- assess the current and likely future state of robotics technology;
- examine the structure of the robotics market, including domestic and foreign users and producers;
- determine how robotics relates to other manufacturing technologies such as computer-aided design and flexible manufacturing systems; and
- determine whether significant Federal policy issues were likely to be raised by the expected growth in industrial robotics.

General agreement was found on the following points:

- the use of robots for industrial automation is growing rapidly; robots are likely to be heavily used by the end of the decade in many settings;
- robotics, while perhaps the most visible and dramatic one, exists in a wide spectrum of technologies that contribute to the automation of manufacturing;
- any major impacts on productivity and employment within this decade will be attributable to the general trend toward automation (including robotics), computer-aided design, the use of information systems to control operations and support managements, and the integration of all these technologies into flexible manufacturing systems; and
- robots, themselves, may have important impacts in the long run as they evolve toward intelligent, stand-alone devices that can perform a variety of complex tasks, and thereby substantially broaden their range of potential application.

II.

Robot Technology

II.

Robot Technology

Roots of Robotics Technology

The paper by Albus (see app. B, item 2) surveys the state of robotics technology. Robots have a dual technological ancestry that has an important effect on discussions about what they are, what they can do, and how they are likely to develop. The two ancestral lines are: 1) industrial engineering automation technology, a discipline that stretches historically over a century; and 2) computer science and artificial intelligence technology that is only a few decades old. Ideas about the nature of robots differ according to the importance given to these two technological roots.

Most modern industrial robots are extensions of automated assembly-line technology. This form of automation has not historically depended on computers, although microelectronics provides a powerful new tool for extending its capabilities. In this view modern industrial robots are closely related to numerically controlled machine tools.

From such a perspective, robotics is already approaching the state of a mature technology. Over the next decade, the most important impacts of robotics on the economy and work force cannot be considered separately from the impacts of industrial automation in general.

On the other hand, modern computer technology may provide future robots with new "intelligent" capabilities such as visual and tactile perception, mobility, or understanding instructions given in a high-level, natural language, such as "Assemble that pump!" The commercial availability of such capabilities may be one or two decades away.

In the view of some computer science researchers, robotics as a technology that will have significant social impact is still in its infancy. They estimate that, given sufficient research support, they could produce a flexible, intelligent robot for the market within this decade. A robot of this type will be able to move freely about an unstructured environment, and perform a wide variety of tasks on command with minimal reprograming time.

This view stresses the need for continuing basic research in computer science related to robotics, particularly in "artificial intelligence." Robots are seen as "stand-alone," reprogramable devices, capable of performing many tasks other than large-scale assembly line applications, for example, small-scale batch manufacturing, mining, or equipment repair.

Which of these views is most pertinent in terms of current policy issues will depend, in part, on whether such an "intelligent" robot would be economically feasible in the near future and whether it would meet a significant need in the industrial sector. It seems likely, in fact, that both types of robotics technology will eventually become important, but that their economic and social impacts will differ to the extent that they are used for different purposes in different environments. Furthermore, the time scale for widespread adoption will be significantly later for the "intelligent" machines.

Definition of Robots

It is difficult to establish a usable, generally agreed on definition of a robot. Experts use different approaches to defining the term. The problem of definition is further compounded for the public by images shaped by science fiction movies that bear no resemblance to robots currently on the market.

At the same time, it is important to have some common understanding of the term in order to define the state of the art, to project future capabilities, and to compare efforts between countries. Depending on the definition used, for example, estimates of the number of robots installed in Japan vary from 3,000 to over 47,000 (5). This variation stems in part from the difficulty of distinguishing simple robots from the closely related "hard automation"* technologies for transferring material.

The Robot Institute of America, a trade association of robot manufacturers and users, defines robots as follows:

> A robot is a reprogramable multifunctional manipulator designed to move material, parts, tools, or specialized devices, through variable programed motions for the performance of a variety of tasks.

This definition seems to describe the current state of the technology and is generally accepted by U.S. industry.

Industrial robots have three principal components:

1. one or more *arms*, usually situated on a fixed base, that can move in several directions;
2. a *manipulator*, the business end of the robot, is the "hand" that holds the tool or the part to be worked; and
3. a *controller* that gives detailed movement instructions.

Computer scientists add to this list a few capabilities that are not generally commercially available today, but that might be part of a general purpose robot of the future (6). They include the following:

4. *locomotion*, some means of moving around in a specified environment;
5. *perception*, the ability to sense by sight, touch, or some other means, its environment, and to understand it in terms of a task—e.g., the ability to recognize an obstruction or find a designated object in an arbitrary location; and
6. *heuristic problem-solving*, the ability to plan and direct its actions to achieve higher order goals.

---

*The term "hard automation" refers to traditional custom engineered automated lines. Although they may contain some standard components, they are built to accomplish one specific set of tasks and often must be completely torn down and rebuilt when the manufacturing process or product design changes.

Technological Context of Robots

The principal technological context of robotics is the field of industrial automation. Most experts on industrial automation state that robots are only one component of a large collection of related devices and techniques that form the technological base of industrial automation (7). This view was expressed both at the workshop and in discussions of experts with OTA staff. Mechanical devices that performed tasks similar to those done by modern industrial robots have existed for centuries. The principal difference is that, whereas so-called "hard automation" is custom designed to a particular task, robots are standardized, but flexible and programable units that can be installed in different environments with much less customization. (Some adaptation is still often required). Clearly, there is a tradeoff between the efficiency of hard automation and the flexibility of robots.

Since machinery will be integrated with the total design of a factory it may not be useful to distinguish robotics as an independent technology. A fully automated factory of the future might include the following components:

- a *computer-aided-design (CAD) system* that provides a tool for engineers to develop new products on a computer using an electronic display screen. The data base generated by the computer during the design phase is then used by other computerized parts of the factory;
- *numerically controlled machine tools* and other automated devices that fabricate components of the product, transport, and assemble them following instructions generated by the CAD system;
- *robots,* also operating under computer generated instructions, that transfer materials from station to station, operate tools such as welders and spray painters, and perform some assembly tasks; and
- *computerized information systems* that keep track of inventory, trace the flow of material through the plant, diagnose problems, and even correct them when possible.

All of the above technologies are currently under development and being used in some form. They will likely evolve into components of a fully automated flexible manufacturing facility.

Thus, there appear to be two parallel technological tracks along which industrial robots are likely to develop: 1) stand-alone standardized units that will have varying uses in many different environments; and 2) robotics technology that is integrated into complete factories that will, themselves, be flexible. Any assessment of the impacts of robotics would need to consider both types.

The Robot Market

The current structure of the industrial robot market—producers, users, and investors—is discussed in detail in the background paper by Lustgarten (app. B, item 4).

The principal uses of robots today are spot welding, spray painting, and a variety of so-called "pick and place" operations that involve simply picking up an object and putting it with a specific orientation in a predetermined spot.

The automobile industry is the largest user of industrial robots, in terms of the value of equipment installed, and probably will continue to be over the next decade. Other major current and potential future users are summarized in the Lustgarten paper. Once again, these estimates consider the industrial robot as an extension of manufacturing equipment. They do not consider possible new applications outside of manufacturing such as mining or equipment repair.

Domestic robot manufacturers appear to fall into four groups:

1. Traditional machine tool manufacturers such as Cincinnati-Milacron that have developed a robot product line.
2. Established firms such as Unimation that have specialized in industrial robots.
3. Large manufacturing firms, such as General Electric and, in particular, electronic computing equipment manufacturers such as Texas Instruments, that plan to be major users of robots and that have decided to build their own. These firms may choose either to retain the technology for their own use or to market their robots externally.

4. Small entrepreneurial firms that develop new, innovative robots. This type of firm has been important in many sectors of the information industry, and could well play an important role in robotics.

The relative importance in the marketplace of these different types of firms will depend on and, in turn, influence the evolution of robotics technology. The history of the microelectronics market suggests that many innovative new types of robots will come from the entrepreneurs, while the large firms will have the capital and capacity to produce and market large quantities of heavy equipment. Also significant in this regard is the trend, common with most high technology firms, toward acquisition of small, innovative firms by larger industrial firms seeking either to diversify or to integrate their traditional product lines with new technologies.

Technology and Market Issues

A number of issues concerning the robot industry were identified in this project:

- *Industrial organization.*—What types of firms will play the most significant role in the production of robots and in innovation? Will robot use and production be concentrated in a few large companies? Will a variety of robotics products be available for many applications by diverse types and sizes of users? What will be the effects on the financial health of different types of potential producers and users?
- *Research and development (R&D).*—Should R&D stress applications or should it focus on fundamental work aiming at significant new breakthrough in the state of the art? What role should the Federal Government play in funding this research via agencies such as the National Science Foundation? What type of work should be pursued in Government research labs such as the National Bureau of Standards, and at what level should it be funded? What additional policies, if any, would be required to stimulate R&D in the private sector?
- *Government use.*—Are there particularly important applications of robots in the Federal Government that should be explored and developed? Experts at the workshop mentioned in particular defense applications and uses of robots for space exploration and oceanographic work.
- *Definition.*—The question of defining robotics and their context, while not a policy issue per se, is an important problem if any Federal action is contemplated to encourage their use or develop any R&D program. How the technology is defined may well determine the type of industry that will be helped by the programs, and influence the structure of the U.S. robotics industry.
- *Standards.*—Should the Government encourage the establishment of technical standards for robotics devices and components? Should standards be set for interfacing between robots and other automation and information technology? Would standards encourage the development of the robot industry and the diffusion of the technology, or would they prematurely freeze the state of the art?

III.

Social Issues

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III.

Social Issues

In addition to the technology and market issues above, the workshop panel identified a number of social impacts. This list is provided in appendix A. Many of the issues on the list were offered without much comment; and, as would be expected, the panel members differed in their opinions of the priority of the various issues and their importance to the Federal Government.

Combining the workshop results with other information collected and evaluated in terms of congressional interests, OTA identified five sets of issues.

- Productivity and capital formation
- Labor
    - —Unemployment, displacement, or job shifting
    - —Positive or negative effects on the quality of working environment (such as exposure to hazards, job boredom, and employer/employee relations)
- Education and training
    - —Need for technological specialists
    - —Need for a technologically literate work force
    - —Need for retraining workers
- International impacts
    - —Import/export of robotics technology
    - —Contribution to economic competitiveness
- Other applications
    - —Military
    - —Space
    - —Oceans

Each of these sets of issues is discussed briefly below.

Productivity and Capital Formation

As stated in the introduction, much of the literature on robotics contains reference to the contribution robotics can be expected to make toward improving industrial productivity. Since a major national concern is the strengthening of U.S. industry, it is important to examine this question.

No answers were agreed on by the workshop participants. However, some experts did warn about making simplistic assumptions that exaggerate the importance of robotics, by itself, in improving productivity. Two reasons were offered:

1. Robotics is only one part of a wide array of technologies available to automate manufacturing and to increase industrial productivity.
2. Productivity is a subtle and complex concept with several definitions and measurements. (This is developed in some detail in the paper by Gold; see app. B, item 3.) Furthermore, even after some specific definition is chosen, industrial productivity depends on many factors that interact with one another. It is difficult, hence, to attribute productivity improvements to any single technology.

These warnings do not suggest that robotics is not an important production technology. Most experts seem to feel that it is. However, they stated that there are dangers inherent in taking an overly narrow definition of the technology when assessing impacts on industrial productivity.

While most applications of robots to date have been made by large firms, the future diffusion of robotics and related technologies can also affect small businesses in several ways. For example, there are likely to be many new business opportunities for small firms to develop and produce software and specialized types of equipment. Secondly, it can be argued that robotics and flexible automation may in some cases lower the minimum scale for efficient production, and therefore that new manufacturing opportunities could be created for small businesses. Third, the adoption of robotics and related technologies by large firms may foreclose some manufacturing opportunities for small firms that cannot afford to invest in new equipment. This situation frequently arises when major equipment technologies change.

Capital formation is another issue that was raised in the workshop and is discussed in the appended Lustgarten paper. The important questions seemed to be whether there would be adequate capital for three purposes:

1. To fund the modernization of industrial plants for the use of automation technology. The financial need would be particularly great if it were necessary to rebuild entire plants in order to make the most effective use of robotics.
2. To fund the construction and expansion of plants to produce robots in quantities necessary to have a significant economic impact.
3. To fund entrepreneurs who wish to develop new types of robots for new applications. The importance of the availability of this type of capital depends on how important it is that the technology be pushed forward rapidly.

No one in the workshop expressed the view that lack of capital is an important impediment to the growth of the robotics industry or to the expansion of the use of robots in manufacturing. However, some panelists observed that a tax policy that encourages such investment would be an important stimulus.

There was some disagreement about the availability of private capital to fund R&D. Robot manufacturers maintained that they were investing large amounts of money in R&D. Other experts suggested that these expenditures were principally aimed at short-term product development and adapting existing products to specific tasks. There was a difference of opinion about the definition of R&D and concerning the amount of emphasis that needs to be placed on long-term research v. short-term product development.

Labor

Unemployment is an issue that is constantly raised in discussions about the social impact of robots, but that seems in this context not to be well understood as yet or even to have been widely studied by labor economists in the United States (8). The discussion at the workshop reflected a wide variety of opinion about the effects on jobs, differences that seemed to be confounded by a number of conceptual problems.

Productivity improvements resulting from the use of robotics and related technologies can affect labor in a number of ways. These effects depend on factors such as the following:

- The effects of new technology on the relative proportion of machinery to workers (the capital-labor ratio) in a given industry.
- The extent of change in prices and production volumes for U.S. firms once the new technology is in use.
- The supply of qualified workers with specific job skills in a given industry.

U.S. employment in a given industry may fall because of productivity improvements, which, by definition, enable fewer workers to produce a given volume of product. U.S. employment in a given industry may remain constant or rise, however, if productivity improvements are combined with increases in production volume. Effective labor compensation may rise or fall if productivity improvements lead to shorter workweeks and/or new product prices, depending in large part on production volume and profitability. Finally, average wage levels will change with changes in the necessary mix of worker skills resulting from the implementation of robotics and related technologies.

Definitions of unemployment, like those of productivity, require distinctions between short-term and persistent job loss, or between true unemployment (job loss) and displacement (job shift).

For some time, most experts in the United States have argued that more jobs are created by new technology than are eliminated. However, if these jobs are in different industries and/or require different skills, the effect on an individual who has been replaced by automation can be traumatic.

Production and servicing of robots and related technologies will create new jobs. The number of jobs created and the rate at which they appear will depend both on the growth rate of the robot industry and the degree to which robot manufacture and repair are, themselves, automated.

Additionally, the effects of modern microelectronics will be to lower cost, improve performance, and widen the availability of automation technology substantially. Negative impact on employment that, in the past, has been small enough to be insignificant or undetectable may be much larger in the future.

In order to assess the effects of automation on future employment levels, a baseline must be established against which job loss or gain can be measured. This baseline could be a simple extrapolation of current trends. But it may also need to be adjusted to reflect two other effects:

- *Virtual employment,* domestic jobs that were not explicitly eliminated, but that would have existed were robots not installed.
- *Virtual unemployment,* domestic jobs that would have been lost if the plant had not responded to domestic and international competition by automating.

As the case with productivity, it is difficult to attribute employment effects to any single component of an entire range of improvements in the manufacturing process, in this case robotics. Any examination of the effects of robots on jobs would need to consider, at least in part, a much broader context of automation technology.

There seemed to be two principal sets of questions concerning unemployment. These questions are different in their focus, in their implication for Federal policy, and in the data collection necessary to analyze them:

1. Will the United States experience a long-term rise in the real unemployment rate due to the introduction of robotics and other automation? If so, will these effects be differentially severe by geographical location, social class, education level, race, sex, or other characteristics? What might be the employment penalty of not automating?
2. Will the use of robots create displacement effects over the next decade? In what ways will these effects be specific to particular industry classes, geographical locations, or types of jobs? How will they effect labor/management negotiations?

Quality of working environment is another issue that was identified. If robots are employed principally for jobs that are unpleasant or dangerous and if the new jobs created by robotics are better, the quality of worklife will improve. Productivity increases may also, in the longer term, result in a shorter, more flexibly scheduled workweek.

New forms of computer-based automation may in many cases relieve job boredom and resulting worker dissatisfaction that many management experts have been concerned with. Workers may be able to make use of more complex skills and perform a greater variety of tasks. For instance, they may be able to follow the assembly of a product from beginning to end and assume greater individual responsibility for the quality of the result.

The human working environment can also be improved by segregating processes that create hazardous working conditions (such as heat or exposure to chemicals) from the section of the factory occupied by humans, and staffing them with robots. Furthermore, equipping a worker with a robot helper for strenuous activities not only eases job stress, but opens up employment opportunities to those who have physical handicaps or other limitations.

Whether these benefits are realized depends, in part, on the particular ways in which industry uses the technology. Many labor experts are concerned that some uses of robots will produce effects on the working environment that will not be so salutary. For example, some argue that one long-term effect of robotics may be to "deskill" labor, requiring less ability on the part of humans as they are incorporated into a mechanized environment.

Some labor experts and others have also expressed concern that automation provides increased opportunities for employer surveillance of employees. Some unions also fear that automation could be used by employers to "downgrade" jobs that require working with automated systems, or that robots might be targeted to replace unionized jobs first.

Education and Training

A number of education and training issues are raised by robotics. Some of them will be addressed in the current OTA assessment of the impact of information technology on education, in the context of vocational education and industrial training.

According to the workshop participants, there is a shortage of trained technical experts in the field of robotics. If there is to be any significant expansion in the pace of automation including robotics, many more computer scientists, engineers, software programers, and technicians will be needed in the next decade.

A shortage already exists in many fields of engineering and science. It seems to be particularly critical in areas of computer software design and programing, according to findings of the recently released National Information System study by OTA (9). Hence, the issue is not peculiarly unique to robotics technology, at least in the case of very highly skilled jobs.

At the same time, the use of robots has already created some new technical jobs. A few programs have been started at the community college level to train workers in robot installation, programing, and maintenance.

Some participants and observers suggested that there was a need for a more technologically literate work force, one that has a basic understanding of technology and mathematics. In their view, improved technological literacy would provide the following benefits:

1. To the extent that workers would be expected to instruct, oversee the operation of, or repair robot units, they would need some basic understanding of computers and systems, both mechanical and electrical.
2. A technologically literate work force would be less likely to resist the introduction of robots and other automation technology.

3. A knowledgeable, technologically skilled worker would be easier to retrain for some other job, somewhere else in the plant.

One observer at the workshop suggested that the reason the Japanese work force seemed to welcome robots in their plants was the high level of technological literacy reported for the average Japanese employee. This characteristic, accordingly, would give the employer greater latitude in finding another and possibly even more skilled job for a displaced worker.

If the introduction of robotics into a plant is not to result in unemployment, a program of retraining displaced workers to take on new jobs may be necessary. Retraining may also be required for those workers who remain, for their existing jobs will change in form and function even if their job title remains the same.

International Impacts

Concern about economic competition in this technology from Europe and Japan was repeated often. Panelists pointed to large investments abroad both for research and development and for encouraging the use of robots. This potential competition exists on two levels: 1) developing and selling robotics technology, itself, and 2) using robots to produce goods more competitively (for example automobiles).

Some experts felt that the directions of robotics-related research were significantly different between the United States and other nations, notably Japan. U.S. researchers emphasize software and highly flexible systems while many foreign laboratories are concentrating on hardware. No one maintained that the foreign state of the art in robotics was superior to that in the United States. "Technological leads" are hard, in general, to either prove or disprove.

There was a general feeling that the utilization of robots was further advanced in several nations (possibly including the Soviet Union) compared to the United States. Some analysis of the Japanese and Soviet picture is presented in the background paper by Aron (app. B, item 1).

The issue of international competition creates conflicts in import/export policy. Controls might be placed on exports of industrial robots either for national security reasons or to limit foreign access to domestic high technology that increases the competitiveness of U.S. firms. However, such controls also deny U.S. robot manufacturers access to foreign markets. Even if the total international market in robots, per se, were to remain relatively small, robot technology would be a vital component in the much larger international market for sales of complete automated factories.

Some issues of export controls are examined in the context of East/West trade in a recent OTA study (10).

Other Applications

Some panelists and other consultants expressed concern that an examination of the impacts of robotics not be restricted only to applications to traditional industrial automation. Because of their ability to work in environments that are hazardous, difficult, or even impossible for a human to enter or survive, there may be future uses of robots that represent new opportunities.

For example, several defense applications were mentioned. While there is work on direct military applications of robots, much of the interest on the part of the defense community in robotics is focused on manufacturing. Improved productivity in the manufacture of weapons and associated military hardware could offer significant savings to the defense budget. Flexible, automated factories, even those not normally involved in military production, could be more easily and quickly mobilized in times of national crisis.

The National Aeronautics and Space Administration is exploring the expanded use of robots for such tasks as planetary exploration, repairing satellites in space, and aiding mining expeditions. Some researchers are interested in the use of robots for ocean exploration and seabed mining.

These examples suggest that, depending on the capabilities of robots in the next decade, there may be important applications that are not now imagined. The nature of these new capabilities, and hence of the applications, will depend in part on Federal policies in such broad areas as R&D, technical education, and reindustrialization.

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Appendixes

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Appendix A

Workshop Issues List of Social Impacts

- **Employment (Plus and Minus)**
  - Displacement
  - Patterns
    - Demographics
    - Skills/Occupational Categories
    - Regional Impact
  - User Industries
  - Quality of Work Life
- **Education and Training**
  - Adequacy of Institutional Structure/Curricula
  - Population Segments
    - General Population
    - Executives
    - Workers
    - Engineers
- **Economic**
  - Economic Incentives
  - Capital Availability and Utilization
  - Antitrust
  - International Competitiveness
    - Import
    - Export
    - Technology Transfer
- **Quality of Life**
  - Income Production and Distribution
  - Product Quality
- **Research and Development**
  - Time Base
  - Continuity
  - Critical Mass
  - Process Over Product
  - People
- **Robotics Technology**
  - General Standards
  - Rate of Diffusion
- **Military Preparedness**

Appendix B

Commissioned Background Papers

The following papers were prepared as background for the workshop and are included for the purpose of documenting the project. Their content and conclusions are the sole responsibility of the authors and do not necessarily reflect the views of OTA:

1. Paul Aron Report No. 25.
2. Industrial Robots and Productivity Improvement by James S. Albus.
3. Robotics, Programable Automation and Improving Competitiveness by Bela Gold.
4. Robotics and Its Relationship to the Automated Factory by Eli S. Lustgarten.

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Paul Aron Report (#25): ROBOTS REVISITED: ONE YEAR LATER

Introduction: Statistics and Definitions

Just about one year ago I issued the Paul Aron Report #22 "Robotics in Japan" which aroused considerable interest as the first serious and comprehensive study by an American analyst. In a note to that Report, I wrote: "Of course, one could continue to search for additional data which would probably improve the presentation. In view of the extensive American discussion of productivity and the spate of articles on robots, excellent though insufficiently attentive to Japan's experience, timeliness demanded the publication of what we know now. Thus, as with all learning, the report must be considered tentative and preliminary not exhaustive". This note could well be descriptive of this current report. This report is an update but to facilitate reading. I have included the relevant material from the previous report. (Report # 22 is still available on request).

In reexamining the conclusions of my earlier effort viewed at the time by some as overly optimistic, I find that the report, while basically correct, understated the tempo of growth. The Japanese industrial robot industry is growing at a faster pace than anyone had previously estimated. The original forecast by the Japan Industrial Robot Industry Association (JIRA) for 1979 shipments was ¥ 36 billion (about $ 180 million); actual shipments amounted to ¥ 42.4 billion, exceeding the original estimate by 17.8%. JIRA had initially estimated shipments for 1980 at ¥ 43 billion; later it revised the forecast upwards by 39.5% to ¥ 65 billion. In actuality, shipments were ¥ 78.4 billion (about $ 392 million) fully 82.3% above the original estimate. JIRA is now estimating shipments for 1981 in excess of ¥ 100 billion (about $ 500 million) and for 1985 approximately ¥ 500 billion (about $ 2.5 billion). For 1990 the current "unofficial" estimate is ¥ 1 trillion (about $ 5 billion). These estimates should be compared with the initial JIRA estimate in early 1980 of ¥ 195 billion for 1985 which many critics argued could not be achieved until 1990. Even JIRA has difficulty keeping up with the forecasts as late in 1980 it was estimating shipments of ¥ 240 - 300 billion for 1985 and ¥ 450 - 600 billion for 1990.

TABLE I

Industrial Robot Production Value

Year	¥ Billion	$ Million
1968	.4	
1969	1.5	
1970	4.9	
1971	4.3	
1972	6.1	
1973	9.3	
1974	11.4	
1975	11.1	
1976	14.1	
1977	21.6	
1978	24.7	
1979	42.4	
1980	78.4	392
1981E	100.0+	500
1985E	500.0	2,500
1990E	1,000.0	5,000

**Exchange Rate: ¥ 200 = $ 1.00

(For convenience only, I have used a single exchange rate of ¥ 200 = $ 1.00 throughout the report for the past, present and future.)

It may be argued that Japanese data on robots is confusing to Americans because of a difference in definitions. The Electric Machinery Law of 1971 in Japan defined an industrial robot as an all purpose machine, equipped with a memory device, and a terminal device (for holding things) and capable of rotation and of replacing human labor by automatic performance of movements. JIRA classifies industrial robots by the method of input information and teaching as follows:

1) manual manipulator--a manipulator that is worked by an operator.

2) fixed sequence robot--a manipulator which repetitively performs

successive steps of a given operation according to a predetermined sequence, condition, and position, and whose set information cannot be easily changed.

3) variable sequence robot--a manipulator which repetitively performs successive steps of a given operation according to a predetermined sequence, condition, and position, and whose set information can be easily changed.

4) playback robot--a manipulator which can produce, from memory, operations originally executed under human control. A human operator initially operates the robot in order to input instructions. All the information relevant to the operations (sequence, conditions, and positions) is put in memory. When needed, this information is recalled (or played back, hence, its name) and the operations are repetitively executed automatically from memory.

5) NC (numerical control) robot--a manipulator that can perform a given task according to the sequence, conditions and position, as commanded via numerical data. The software used for these robots include punched tapes, cards, and digital switches. This robot has the same control mode as an N.C. machine.

6) intelligent robot--this robot with sensory perception (visual and/or tactile) can detect changes by itself in the work environment or work condition and, by its own decision-making faculty, proceed with its operation accordingly.

I have used three different robot definitions:

(1) "Robots by Japanese Definition"--all 6 classes

(2) "Robots by U.S. Definition"--classes 3, 4, 5, 6

(3) "Sophisticated Robots"--classes 4, 5, 6

The American Robot Industry Association (RIA) defines a robot as "a manipulator designed to move material, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks." Thus, the U.S. definition of robots eliminates the manual manipulators and fixed sequence machines.

The following is a breakdown by the nature of input information and teaching (in yen value).

Daiwa Securities America Inc.

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TABLE 2

Share in Total Shipment

By Nature of Teaching and Input Information

	1974	1975	1976	1977	1978	1979	First Half F.Y. 1980
1) Manual Manipulator	6.5%	7.8%	11.4%	8.7%	5.6%	5.0%	7.8%
2) Fixed Sequence Robot	68.0	73.0	47.6	39.0	37.1	47.0	35.8
3) Variable Sequence Robot			8.9	10.9	14.6	18.0	13.3
4) Playback Robot	10.5	10.2	12.7	18.0	17.4	17.0	25.0
5) NC Robot	0.2		0.4	0.4	0.5	4.0	2.6
6) Intelligent Robot	0.1	1.7	6.2	10.3	12.2	9.0	9.9
7) Attachments	14.7	7.2	12.8	12.7	12.6	----	5.6
	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The sophisticated robots clearly represents an increasing share of production--37.5% by the first half of 1980 compared to only 10.8% in 1974.

Data is available for the number of units per type produced in 1979 and the number of robots installed and working at the end of 1979.

TABLE 3

Shipments of Industrial Robots - 1979

Type	Units	Value (¥ Million)
Manual Manipulator	1,051	2,100
Fixed Sequence Robot	10,721	19,990
Variable Sequence Robot	1,224	7,700
Playback Robot	662	7,200
NC Robot	89	1,700
Intelligent Robot	788	3,800
	14,535 units	42,400

TABLE 4

Industrial Robots - Installed and Operating

12/31/79

Manual Manipulator	7,290
Fixed & Variable Sequence Robot	45,760
Playback & NC Robot	2,410
Intelligent Robot	788
	56,800 units

As JIRA previously had not differentiated fixed and variable sequence robots, the number of operating variable sequence robots installed in 1979 must be estimated. I prefer the more conservative estimate of 4300 rather than the higher 10,250.

Final data is not yet available for 1980 but, based on the latest preliminary data shipments and installed working robots at the end of 1980 can be estimated as follows:

TABLE 5

Industrial Robots - Installed and Operating (Estimated)

12/31/80

		Units
1)	Manual Manipulator	8,790
2)	Fixed Sequence Robot	56,460
3)	Variable Sequence Robot	6,100
4&5)	Playback & NC Robot	3,460
6)	Intelligent Robot	1,690
	Total	76,500

TABLE 6

Shipments of Industrial Robots Estimated

1980

		Units
1)	Manual Manipulator	1,500
2)	Fixed Sequence Robot	15,000
3)	Variable Sequence Robot	1,800
4)	Playback Robot	900
5)	NC Robot	150
6)	Intelligent Robot	350
	Total	19,700

Using the more restrictive U.S. definition of industrial robots, the following chart compares the relative positions.

TABLE 6A

U.S. - Japan Comparison

Industrial Robots

1980

	Japan	U.S.
Production in Units 1980	3,200	1,269
Production in Value ($ Mil.) 1980	180	100
Installed Operating Units 12/31/80	11,250	4,370

The most optimistic estimates for U.S. production in 1980 is 1,500 and for U.S. installed robots 5,000 but even if this estimate were correct the U.S. position is hardly altered.

In 1980 the United States probably placed third in the unit production of industrial robots--the Soviet Union produced an estimated 2,000 - 3,000 industrial robots. Soviet production, however, tends to concentrate on the less sophisticated robots. Somehow, Americans seem to have taken comfort with an estimate published in Time in December 1980, of 25 robots in the Soviet Union (at the very moment that the Soviet Union was producing about 70 different robot models). Incidentally, Soviet robotics began even later than Japan--in 1971-72 the first three Soviet robots were produced. The United States produced its first robot in 1961--a Unimate based on a patent originally issued in 1954. It was only in 1967 that Tokyo Machinery Trading Co. started to import and sell a Versatran robot, then produced by AMF, Inc. In November, 1968, Kawasaki Heavy Industries concluded a technology license agreement with Unimation and in 1969 began to produce robots in Japan. Thus, the U.S. enjoyed at least an eight year lead over Japan and a ten year lead over the Soviet Union.

What does the future hold?--My estimates or better "guestimates" for Japan is necessarily very tentative.

TABLE 7

Japanese Industrial Robot Demand Forecast--Paul Aron

In Units

	1980(E)	1985(E)	1990(E)
Manual Manipulator	1,500	6,000	12,000
Fixed Sequence	15,000	30,000	45,000
Variable Sequence	1,800	14,000	18,650
Playback	900	6,500	13,000
NC Robot	150	1,400	2,800
Intelligent	350	10,000	23,000
Total	19,700	67,900	114,450

TABLE 8 (Japanese Industrial Robot Demand Forecast--Paul Aron[cont.])

In Value - Billion ¥

	1980(E)		1985(E)		1990(E)	
	(¥)	(%)	(¥)	(%)	(¥)	(%)
Manual Manipulator	3.0	3.8	10	2	20	2
Fixed Sequence	38.4	49.0	60	12	90	9
Variable Sequence	12.0	15.3	75	15	100	10
Playback	12.1	15.4	70	14	140	14
NC Robot	3.7	4.7	15	3	30	3
Intelligent	4.9	6.3	120	24	280	28
Auxiliary Equipment	3.0	3.8	70	14	140	14
Export	1.2	1.5	80	16	200	20
Total	78.4	100 %	500	100%	1,000	100%

Using the more restrictive American definition of robots, Japanese industrial robot production is estimated to achieve a unit output of 31,900 with a value of $ 2.15 billion in 1985 and 57,450 units and $ 4.45 billion in 1990. If this were to occur, Japanese output in 1985 would be four times greater in units and value than the most optimistic forecast for the U.S.

Why have industrial robots enjoyed such success in Japan and why do the Japanese place such high confidence in their future?

LABOR:

Japan's success in robot production and installation can be traced, in large measure, to its labor practices. The Japanese employees in major corporations are guaranteed lifetime employment (until the age of 55-60). In addition, all employees receive two bonuses, each ranging from 2-5 months pay, in June and December, which, while negotiated between the union and management, are ultimately based upon the company profitability. The Japanese union is not based on crafts, skills or occupations: the union is on a company wide basis and covers all member of the bargaining unit. Employees identify with the company, not with a skill and they are often shifted from one job to another within the company. The worker, not fearing loss of employment, does not oppose automation; in addition, as automated production generally enhances quality and profit and consequently the bonus, the Japanese employees welcome the robots. In Japan the company assumes the responsibility for retraining the employees who have been displaced by the robots. The large companies, at least in the last 20-25 years have assumed the responsibility of training and retraining their employees; lifetime employment deprives most companies of the opportunity to recruit skilled workers from other companies and therefore, necessitates training. Not fearing the loss of trained workers, companies are encouraged to devote considerable effort to training programs. Finally, as robots are used in dangerous, unhealthy and repetitive jobs, the employees consider production by robots as a means of relieving monotonous and environmentally harmful tasks in manufacturing. Employees, displaced by robots, have moved to jobs, more challenging intellectually and less demanding physically.

The practice of QC circles has played an important role in developing employee participation in problem-solving. They are voluntary teams of 8-10 employees who began in the mid-sixties to study quality problems and to suggest improvements. These teams expanded their range of activity from quality to many other areas including productivity, especially during the seventies. Studies indicate that both the unions and particularly the QC circles have often been involved in introducing robots into plants. It should be no surprise that those companies which have the most active QC circles are also the leaders in robotization. Of course, the relatively high tempo of real economic growth in Japan, with its consequent demand for increased labor, has more than compensated for the losses of jobs resulting from increasing productivity, automation, and robot introduction. Some Japanese economists, however, are already warning that the saturation by industrial robots might create an unemployment problem in the 1990's.

The Japanese seem to believe that they displaced the U.S. as the "Number One" in robot production largely because of the labor problem. In America and Western Europe, the introduction of robots is frequently debated and the crucial point in such debates is the unemployment problem. This is rarely discussed in Japan and instead the positive effects of robots are discussed: improvement of quality and productivity and greater safety for the employees. Stress is placed on the new opportunities for greater and higher level employment, as robot operators, robot maintenance workers, and "software engineers", and for opportunities in new industries such as ocean resource gathering made possible by robots. Unlike Japan, few U.S. companies have assumed the responsibility for retraining workers that could be displaced by robots. Furthermore, the American worker does not directly benefit from the increased savings and profit created by robotics. It is interesting that the TV program on productivity ("If Japan can do it, etc.") omitted any discussion of the bonus in Japan.

COSTS OF LABOR AND ROBOTS

The advantages of industrial robots can be better understood in the context of the relationship of labor costs and robot costs. The accomplishments of the robot introduction in Japan from 1968 to 1973 were not promising because of the wide divergence of labor and robot costs. Before the 1973 "Oil Shock", Japanese labor costs were still relatively inexpensive while industrial robots were still high-priced because of the low level of electronic development. During the decade of the seventies labor costs rose sharply in Japan. The manufacturing cost of industrial robots of all types at first declined from 1970-1975. After 1975, the price of the simpler and less electronic "robots" rose, but the "semiconductor revolution" in Japan continued to reduce the cost of the more sophisticated robots. The following table based on a JIRA survey is revealing.

TABLE 9

Ratio of Robot Costs to Labor Costs

(Unit - ¥ 1000)

Total		1970	1975	1978
A.	Labor Cost Per Man	990	2,300	3,000
B.	Average Price -- Robot (Japanese definition)	4,600	4,100	5,000
C.	Cost -- Playback Robot	12,000	11,000	11,000
	Ratio B/A	4.6	1.8	1.7
	Ratio C/A	12.1	4.8	3.7

The decline of robot costs relative to labor costs is especially sharp in the field of sophisticated robots. Superficially, a playback robot can be amortized within four years on a single shift and within two years on a double shift. The actual expenses of robot installation and maintenance resulted in a slower rate of amortization. In the future, labor costs are expected to increase 6 - 7% annually while robot costs, thanks to declining microprocessor prices, should remain level or decline.

In a questionnaire distributed by JIRA on the motives for installing industrial robots in the future, the responses in order of importance were as follows: (1) economic advantage, (2) increased worker safety, (3) universalization of production systems, (4) stable product quality, and (5) labor shortage.

Hence, the economic advantage of the industrial robot over human labor which seems certain to grow in the future is considered the most important factor in the increased application of industrial robots.

MANAGEMENT

Japanese management on all levels has been more responsive to the introduction of robots than their American counterparts. Life-time employment has created greater security and a more long-range attitude among Japanese managers. The absence of stock options reinforces this attitude. Japanese managers are able to tolerate the high initial costs of incorporating robots into production and are willing to accept a much longer payoff than their American counterparts. In the first year of robot introduction, costs can be very high--not only increases in depreciation, interest costs, and miscellaneous costs related to the robot (changes in the plant and its equipment to accomodate the robots), but also interference and slowdowns in production while the robot is being fully integrated into production. In one case study in Japan, for example, the company had anticipated that robots would increase production, and thus would permit write-off of all costs within the first year. Instead, production declined and total costs grew by 30%. Similar experiences have caused many American managers to abandon their robot program. But the Japanese persisted and at the end of the second year total costs were 25% less than if the product had continued to be produced manually.

Japanese managers are generalists, often shifted from one area to another that bears little relationship to their previous experience. On the other hand, American managers tend to be specialists and stay within one area of work during their entire career. This, at times, creates opposition, if not hostility, to a novelty such as a robot that might undermine their position. American reports are replete with tales of opposition to robots by middle and lower managers and conflicts between manufacturing engineers seeking to introduce new technology and production departments seeking to maximize current production and intolerant of any interference in output. Even the front line of management-the foreman-often see the robot as a threat to their status especially when the robot requires "care and feeding" by an inexperienced youth with a training in electronics who substitutes knowledge for strength.

In an atmosphere of relatively high interest rates the financial side of U.S. management constantly seeks shorter and shorter payouts and American roboticists often see these "bean counters" as their enemy. The non-adversary relationship and the long-term outlook which pervades the Japanese company has successfully coped with the issues of robot introduction.

American and European companies were also, to some extent, sidetracked in robotics as they had been in the production of numerical control machinery. The Americans developed very expensive and very complicated NC machines so that when the computer broke down, the entire machine, virtually a machine shop in itself, halted. The Japanese developed smaller, simpler, less expensive machines that catered to small-scale production and could produce in small batches. In robotics the European and American producers often concentrated on the most expensive robots and permitted the Japanese to develop robotics gradually from the unsophisticated manual manipulators to more complex systems that incorporate "intelligence".

INDUSTRY STRUCTURE FOR INDUSTRIAL ROBOTS

At present about 130-140 firms in Japan are manufacturing robots of whom 37 are members of the JIRA. Most large manufacturers, actual or potential, are JIRA members but some important exceptions should be noted--Matsushita Electric Industries, Osaka Transformer Corporation, Seiko, and the pen manufacturers.

The existing robot makers are widely distributed over the whole range of business scales. In size of capitalization, robot makers are broadly distributed from small firms to giant corporations. In examining the table below, the 55 small companies with less than ¥ 100 million capitalization (equal to about $ 500,000) represents 41.4% of the enterprises; the medium firms with (¥ 100 - 300 million) represent 23.3%, while the firms with over ¥ 3 billion capitalization (equal to about $ 15,000,000) represent 35.3% of the corporations. The same trend is evident when we examine the robot makers by number of employees. The small firms with less than 500 employees represent 46.6% of the total, the medium firms with 500 to 5000, 30.1%, and the giant firms with over 5000 employees, 23.3%. This data, based on a JIRA survey in 1979, of 133 robot makers, is shown below:

TABLE 10

Industrial Robot Maker Distribution

By Size of Capital

Less than ¥ 10 million	19 companies	14.3 %
¥ 10 million - ¥ 100 million	36 companies	27.1 %
¥ 100 million - ¥ 1 billion	23 companies	17.3 %
¥ 1 billion - ¥ 3 billion	8 companies	6.0 %
More than ¥ 3 billion	47 companies	35.3 %
Total	133 companies	100.0 %

TABLE 11

Industrial Robot Maker Distribution

By Number of Employees

Less than 50	33 companies	24.8 %
50 - 500	29 companies	21.8 %
500 - 1000	15 companies	11.3 %
1000 - 5000	25 companies	18.8 %
More than 5000	31 companies	23.3 %
Total	133 companies	100.0 %

The wide distribution of industrial robot makers is the result of several factors. The giant electrical equipment and heavy machinery makers were attracted by the high growth potential of industrial robots and entered the field to diversify their business. Many have been motivated originally by the need for robots within their own business to increase productivity and safety, overcome shortage of some skilled workers, and to enhance their ability to undertake small and medium batch multi-product manufacturing. This applies to the large electrical manufacturers such as Hitachi, Matsushita, Toshiba, Mitsubishi Electric and Fuji Electric. It also applies to the heavy equipment manufacturers such as Kawasaki Heavy Industries, Mitsubishi Heavy Industries, Tokico, Shinmeiwa, and Ishikawajima-Harima. Some of the steel makers such as Kobe Steel and Daido, in diversifying their operations into heavy machinery, also were attracted to robots.

Since robot application often must be custom-made for each and every user according to his specific production process, the robot maker, even if small, can specialize in a specific area of application and successfully compete with the big corporations. Some of these smaller companies undertook to produce robots in order to enhance their major products such as Aida in the hydraulic press manufacturing. The production of robots often enabled the manufacturer to offer a total system rather than an individual piece of equipment. This phenomenon is seen mainly among the machine makers such as Fujitsu Fanuc, Toshiba Seiki, Nachi-Fujikoshi and Komatsu. Other small enterprises began to manufacture robots for their own use and then ultimately marketed them. This applies to firms such as Seiko and Sailor Pen. Many firms branched into robots from manufacturing materials handling equipment and conveyors. This included firms such as Tsubakimoto and Motoda.

The Japanese are currently debating the future of this structure of robot makers. Some expect no radical change in the industry structure within the foreseeable future. They believe that the small to medium enterprises will continue to carve out markets for themselves in the many specialized areas. Others visualizing the increasing role of minicomputers and intelligent robots expect that the large electric manufacturing companies because of their superiority in IC and LSI technology, will dominate the robot industry. At present, each individual robot maker has its own area of special expertise such as Yaskawa in arc welding, Kobe Steel in large paint sprayers, Aida in press application, Fujitsu Fanuc in machine tool processing. However, all makers are using the technology developed in their specialty area for applications of other areas. Kawasaki is the most active in this approach with its Unimates entering almost all areas of application. But many other manufacturers are aspiring to be "universal robot makers". The emergence of an electronically-oriented universal robot maker depends on the rate of development of intelligent assembly robots.

Unlike the United States, where two robot makers hold over one half of the market share, the Japanese market is widely dispersed and changing each year. In the U.S., despite the many new companies entering the field, companies actually manufacturing robots probably number less than 20 compared to about 140 in Japan. Kawasaki Heavy Industries has only 3-4% of unit volume of all Japanese robots (by Japanese definition). By the more strict U.S. robot definition, Kawasaki produced 450 of the 3300 robots made in Japan in 1980 for a market share of 18% in units. Because of its relatively higher price, the market share of Kawasaki in value is probably somewhat higher. In many respects the production of robots in Japan resemble the fierce competition that grew up among manufacturers of television sets, digital watches, desk and hand calculators and videotape recorders. After a period of intense competition among many firms, production ultimately was concentrated in a few large firms. It should be noted that this period of competition also resulted in Japanese domination in the world market for these products. As the spokesman for the Long Term Credit Bank of Japan confidently puts it: "It is only a matter of time before the industrial robot becomes one more piece of merchandise which symbolizes Japan".

This industrial structure has given the Japanese several advantages. The American robot manufacturers must sell their robots to users; few can test their equipment in actual production conditions at their own plants. With the entry of IBM, Texas Instruments, GE and Westinghouse into the robot market, this should be altered. But in Japan all through the decade of the seventies the major manufacturers now emerging-Hitachi, Matsushita, Toshiba-had been using robots within these companies. Furthermore, many other companies entered the robot field because they had developed robots initially for their own needs-Sailor Pen, Pentel, Pilot in the pen and pencil industry, Okamura in the furniture industry, Tokico in the compressor industry. Many companies developed robots to sell their own products-Aida, Japan's leading press manufacturer , developed a series of loading and unloading robots for its presses. Fujitsu Fanuc developed a series of robots to service their N.C. machines. In turn, Fanuc's competitors developed robots to stay in competition with Fanuc while Fanuc in turn developed an assembly robot to help reduce the costs of producing its robots. In some cases companies developed robots for affiliates. That Mitsubishi Electric should develop a "Window Cleaning Robot", a fixed sequence machine for high buildings, can be better understood when we know that its sister, Mitsubishi Estate, owns many of the tall buildings in Tokyo's Wall Street. This automatic cleaning operation, reduced maintenance cost, eliminated dangerous work, provided better cleaning, and protected "privacy in offices, hotels, and other places". Toyoda Machine Works provided welding and handling robots for Toyota. Mitsubishi Heavy Industries provided robots originally just for Mitsubishi Motors, its automobile making subsidiary.

Because the robots were used within their own factories, the robot makers in Japan offered for sale not just robots but total systems which already had been tested for several years in their own factories. This compelled companies that had originally just produced robots to begin to develop total systems. One example of this is a completely unmanned computer-run dry noodle factory-which includes an automatic warehouse, battery-operated cars, loading and unloading robots, automatic manufacturing and inspection, and packing.

GOVERNMENT POLICY

It is quite evident that MITI has been interested in robots since the beginning of the seventies. It would seem unlikely that JIRA would have been formed without some government encouragement. However, it was not until 1978 that the industrial robot was officially designated as an "experimental research promotion product" and as a "rationalization promotion product" with promulgation of the special Machine Information Industry Promotion Extraordinary Measures Act. While the Electric Machinery Law in 1971 had defined an industrial robot, industrial robot terminology was first standardized in 1979 under the Japanese Industrial Standards.

Following the typical policy of cooperative rather than adversary relations with business, the Ministry of Trade and Industry (MITI), having identified robot production as a major strategic industry for Japan's future, undertook several measures to popularize their utilization.

(1) With MITI encouragement, if not direction, a robot leasing company, Japan Robot Lease, (JAROL), was founded in April, 1980 with the initial paid-in capital of ¥ 100 million. This company is jointly owned--70% by 24 JIRAmembers and 30% by ten non-life insurance companies. The aim of JAROL is to support robot installation by small and medium-scale manufacturers and increase their productivity. As 60% of operating funds are financed by low cost loans from the government's Japan Development Bank, and the rest from the Long-Term Credit Bank, Industrial Bank of Japan and the city banks, JAROL is in a position to lease industrial robots under conditions more advantageous than the ordinary leasing companies. For its first year of operation (fiscal year 1980), JAROL planned ¥ 700 million robot leases; actually its leasing contracts numbering 52 amounted to ¥ 1,150 million (about $ 57½ million). The average term of the lease was 6.5 years and provided a full payout. In April, 1981 JAROL offered a more flexible 2 - 3 year rental agreement (not a full payout) and after the expiration of the agreement planned to rent the robot to the same or a different user. At the same time JAROL began discussions with MITI to enter overseas leasing of robots. This resulted from a request of an Australian firm to lease Japanese-made robots. Some question arose as to the propriety of using government loans for overseas leasing but JAROL suggested loans from the Japan Export and Import Bank. Positive action on this matter will greatly strengthen Japan's competitiveness in overseas industrial robot markets.

(2) MITI has arranged for direct government low-interest loans to small and medium-scale manufacturers to encourage robot installation for automating processes dangerous to human labor and for increasing productivity. The government budgeted for fiscal year 1980 ¥ 5.8 billion for these loans which are extended through the Small Business Finance Corporation, a government finance agency.

(3) MITI has permitted the manufacturer who installs a robot to depreciate 12.5% of its initial purchase price in the first year in addition to taking ordinary depreciation. This extra depreciation is a common practice in Japan when MITIseeks to promote a particular industry or product. Extra depreciation has been as high as 50%. Generally it can be taken over a three year period and is usually repaid in five annual installments beginning in the sixth year. By installing an industrial robot, a firm can depreciate 52.5% in the first year, 12.5% plus 40% (5 year depreciation double declining).

(4) MITI created an atmosphere favorable to the introduction of the industrial robot, but it had depended largely on the private companies to determine the direction and scale of production and to undertake R & D. However, MITI has now just announced plans for a huge R & D program to be discussed in the following section.

ORGANIZATION OF ROBOTIC RESEARCH AND DEVELOPMENT

Research on robotics in Japan is conducted by three major types of institutions- colleges and universities, national and public research institutes, and research laboratories of private firms. The number of robot research laboratories in universities and public research institutions grew from 43 in 1974 to 85 in 1980. In fiscal 1979, the universities spent 100 million yen (or about $.5 million) on robot research and the public research institutes about 220 million yen (about $ 1 million). This total of about $ 1½ million is hardly a very large amount. But this statistic omits "personnel expenditures" and is therefore a substantial understatement. Some 270 researchers at colleges and universities and 80 researchers at institutes worked on robots in 1979. Public research has concentrated on theoretical problems, many of which have direct and immediate application such as--speed control (acceleration of robot when its gripper holds nothing), improved positioning accuracy, simplification and modularization of robots, sensory perception, pattern recognition ability.

The expenditure of private enterprises on robots has not been made public but up to now has been the overwhelming source of robotic R & D. Of the 107 robot manufacturers surveyed by JIRA in 1979, twenty had a specialized robot research division in their in-house research laboratories, while another fifty-two without a special robot research division had one or more researchers specializing in robot research.

The private research laboratories have concentrated on R & D most closely linked to application--increased speed, miniaturization, computer control, weight reduction and modularization (development of interchangeable robots).

A major change has just occurred--MITI announced a seven year ¥ 30 billion national robot research program to begin April 1, 1982. MITI will create a new R & D group to carry out the program whose purpose is to make robots suitable for a wider application and to develop Japanese robot technology instead of relying on imported American and West European know-how. Stress is to be placed on intelligent robots especially for assembly work, and on robots for nuclear, space, oceanic, and earthmoving industries. The development of sensory perception, language systems, and motional capacity are to receive top priority. This program is called a nationally important major technology development scheme.

SOCIO-ECONOMIC IMPACT OF INDUSTRIAL ROBOTS

This section expresses the Japanese views on this topic and is greatly indebted to Mr. Yonemoto of JIRA, Japan's most prominent authority on this subject. Industrial robots have three major characteristics which, in large measure, determine their socio-economic impact.

1) Industrial robots, unlike special purpose automated machines, are programmable, and, as a consequence, are both flexible and versatile. A robot's movements may be altered merely by changing its program.

2) Industrial robots can perform beyond the physical and mechanical abilities of humans. They do not tire from long and continuous hours of work in an environment which may be uncomfortable, if not hazardous to humans. (They require no breaks to overcome fatigue or to meet personal needs).

3) Industrial robots perform with a high fidelity and accuracy in compliance with the instructions which they receive from man.

As a result of their versatility, super-human capability, and high fidelity to programming, industrial robots have changed in many ways the production scene in which they are employed.

1. Automation of Multi-Product Small Batch and Mixed-Flow-Production Line.

The flexibility and versatility of industrial robots makes possible the automation of multi-product small batch and mixed-flow-line production. The special purpose automated machine is restricted to limited model mass production. Recently, consumer demand has become increasingly diversified to the point where according to Japanese estimates, fully 80% of mechanized industry's products are manufactured in a moderate-to-low volume of output. Thus, the nature of contemporary consumer demand and particularly Japan's desire to accomodate a wide diversity of export requirements necessitated and encouraged the use of industrial robots.

2. Ease of Phasing in Product Design Modification and Model Changeover.

A complete changeover or even a modification in a product model often require changing or at least radically rebuilding a special purpose automated machine. Where an industrial robot is used instead, a mere change in program is required. As the product life cycle shortens, the flexibility and versatility of industrial robots becomes increasingly advantageous.

3. Improved Operating Ratio and Increased Operating Time.

Unlike men, industrial robots can operate on a 24 hour basis and therefore, the machines, they service can also operate on a 24 hour basis. Furthermore, industrial robots are capable of performing functions at a high speed which exceed human limitations.

4. Ability to Withstand Severe Working Conditions.

The industrial robot can work in an environment which is adverse to humans. Human beings require a host of conditions to make the working atmosphere both pleasant and safe-ventilation, proper lighting, air conditioning, or at least temperature control, and a variety of safety devices and conditions.

5. Ability to Execute Proper and Accurate Motions and the Ability to Cope Elastically with Changing Production Volume.

The sustained stability of industrial robot operation--their ability to work continuously and accurately faithful to their man-given instructions--eliminates slumps and spurts and provides a smoother production flow. This ability also enables increased production demands to be met effectively.

6. Change in Nature of Production System.

To the Japanese the introduction of industrial robots means a change in the production system. In the typical traditional mass production line the machine determines the activity of the operators--something pointedly satirized in Chaplin's famous film, "Modern Times". The operator programs the industrial robot and therefore, the human dominates the system. According to the Japanese, the industrial robot reduced psychological resistance to the conveyor system and thus permitted its more effective use. They believe that human satisfaction derived from the human control over the robot and this attitude led to qualitative improvement in labor.

7. Creation of New Technologies.

The characteristics of the industrial robots--combined with the change in the production system to a man-dominated robot-machine system led to the creation of completely new technologies and to their application in exploiting oceanic resources and in increasing utilization of nuclear energy. Robot applications to health, household, and cleaning duties have also been forecast.

The wide socio-economic impacts of the application of industrial robots expected by the Japanese roboticists has begun to be evident.

1. Improvement of Productivity.

The automation of small-batch and multi-product mixed-flow line production saved man-hours and reduced in-process and accumulated inventory. The improved operating ratio and increased operating time also reduced man-hours. The relative ease with which an industrial robot could be fit for a product design changed saved the time usually required for retooling. The more effective use of the conveyor system made possible by the industrial robot, also contributed to enhanced productivity.

2. Stability and Improvement in Product Quality.

The super-human capacities of the industrial robots and their fidelity to human instruction led to a uniformity of products and hence made possible the stability and improvement of product quality. By working 24 hours the industrial robot eliminated the incidence of inferior or defective products which often occur during factory start-up operations. The quality variations which result from long hours or the differing abilities of operators were eliminated.

3. Improvement in Production Management.

Production management has improved for several reasons:

a) Reduction of inventory and in-process products as a result of automation of small-batch and multi-product mixed-flow-line-production.

b) Reduction in set-up time and elimination of retooling the production line.

c) The durability and accuracy of industrial robots facilitated production planning.

d) Industrial robots reacting more elastically to production volume change reduced problems of manpower reallocation.

e) Industrial robots have helped to improve the quality of work life and led to greater employment stability. In addition, they have contributed to overcoming the skilled manpower shortage in such areas as welding and painting.

4. "Humanization" of Working Life.

a) Industrial robots released humans from hazardous and unhealthy working conditions preventing accidents and occupational diseases.

b) Industrial robots released humans from monotonous work and thus reduced psychological stress.

c) The man-robot-machine production system eliminated the psychological resistance to the conveyor system, and improved labor quality and human satisfactions from the human control of robots. Such a system corresponded better to a more highly educated and aging society. In recent years, Japan's society has witnessed a growing shift from blue-collar to white-collar occupations and the industrial robot enables corporations to accomodate to this trend. Human resources liberated from adverse work environments and from monotonous repetitive manual jobs are rechanneled into more intellectually demanding robot operations and maintenance positions. For example, manual wire bonding of IC's require the fatiguing performance of monotonous, repetitive tasks under a microscope, and a training period of 4 - 5 months. The industrial robot reduces the training period to 15 minutes and eliminates the fatiguing manual operation.

Robot utilization makes possible greater employment opportunity for the infirm, elderly and female work force in industries where heavy and continuous loading/unloading or carrying a heavy welding gun were required. The "humanization" or work life contributed to employment stability, reducing absences from work.

5. Resource Conservation.

Industrial robots contributed to conservation of resources, a high priority factor especially since the oil crisis of 1973. These savings were achieved in a variety of ways:

a) The robot saved material-the paint spraying robot, for example, used 20-30% less than the manual painters in many operations.

b) The ease of accomodating the robot to product design changes reduced investment in purchasing and/or rebuilding equipment.

c) The reduced defective ratio saved resources.

d) The industrial robot, by working in unpleasant environment, reduced the energy consumption of air conditioning, ventilation, lighting, etc.

d) By its ability to operate on one, two or three shifts, the industrial robot resulted in reducing investment.

ROBOT APPLICATION

Robot shipments are also classified by user which shows the automobile as the primary buyer except in 1980, when the electric appliance industry, which usually occupied second place, took the lead for the first time.

TABLE 12

Breakdown of Industrial Robots by User (In Value)

Japanese Definition

	1974	1975	1976	1977	1978	1979	1980P
Auto	35.5%	19.9%	30.5%	33.6%	34.5%	38.4%	30.0%
Electric Appliance	9.6	12.8	20.9	23.1	24.6	17.5	36.0
Machinery	4.5	5.6	7.6	8.8	7.0	5.3	
Metal Products	5.8	3.8	5.8	3.4	7.1	9.0	
Exports	2.9	4.2	2.3	4.5	2.5	1.9	

(P - Preliminary announcement of JIRA)

However, the automobile industry still dominated the sphere of sophisticated robots.

TABLE 13

Shipments of Playback Robots by User

(4/1/80 - 10/1/80)

	Unit	Value
Automobile	61.5%	52.4%
Electric Appliance	10.3	11.6
Machinery	3.9	8.3
Metal Products	4.4	5.7
Exports	5.9	6.0
Others	14.0	16.0

The large percentage of exports of playback robots compared to the less than 2% export share of total industrial robot production indicates the direction of Japan's export policy.

Since the playback robot seems to be concentrated heavily in the automotive industry, an analysis of the type of work performed by playback could indicate relative use:

TABLE 14

Breakdown of Playback Robot by Work Process

(4/1/80 - 10/1/80)

	Unit	Value
Arc Welding	18.8%	26.0%
Spot Welding	57.1	45.1
Spray Painting	11.3	17.8
Others	12.8	11.1

It is clear that spot welding represents the major application of the playback robots. A preliminary report on 1980 calendar year robot production revealed that compared to 1979, arc welding robots increased 211% in value and 100% in units, and spot welding robots grew 85% and 100% respectively. In addition, assembly robots grew 340% and 33% respectively (certainly from a low base), and press and conveying robots 60% and 6% respectively. The large growth in assembly robots was mainly for insertion of electronic parts into printed circuit boards (an increase of 440% in 1980 compared to 1979).

SPOT WELDING

The automobile industry has until 1980 been the largest single consumer of robot production, in large measure because of its purchases of spot welding robots. The majority of Japanese car bodies consist of 300-400 press-formed parts manufactured from sheet steel which are bonded together by 3,000-4,000 spot welds. In the latter half of the 1960's special purpose automatic multi-spot welding machines were introduced. However, with the tendency to product diversification and the shorter life cycle of car models, the return on investment of the multi-spot welders declined. Large monetary expenditures to modify the multi-spot welders were necessitated by model change-over or design modification. During the modification, a considerable period of time was lost and management expenses were consumed for production line reorganization.

Thus, the robots replaced the multi-spot welders because they only require being taught where to weld in the new model in the event of a model change-over. Often merely one hour is required for the new learning process. As production volume is no longer clearly predictable, it became quite risky to invest in special purpose automatic machines.

investment in the more flexible robot seemed preferable. The robot also eliminates the need of the manual operator to follow the conveyor line with a heavy welding gun.

The automobile companies then introduced batteries of robot welders. In some assembly plants, a single operator for robots can handle a work load once shared by ten workers. To improve productivity by simultaneous multi-spot welding, efforts have been made to develop multi-arm welding robots and to apply a number of modular robots to welding. Robot introduction into the spot welding line has made possible the automation of multi-product mixed-flow-assembly line on which various model flow one after another.

Nissan has been the largest user of spot welders and by the end of 1980, it had about 300 spot welders. At the same time, Toyota reportedly had 200 spot welding robots, but it ordered 720 robots from Kawasaki Heavy Industries--220 by 3/81, 200 by 3/82, and 300 by 3/83. It has been assumed that most of these would be used for spot welding. Kawasaki is reportedly delivering about 25 units monthly. Mitsubishi Motors has been receiving spot welding robots from Mitsubishi Heavy Industries. Toyo Kogyo and Honda have introduced welding robots.

Kawasaki H.I. is clearly the leader in production of robot spot welders. By spring of 1981, it had delivered 1,500 Unimates primarily for spot welding, and its monthly production rate is 60. Mitsubishi H.I. occupies second place, having delivered 250 robots by the spring of 1981 and with a monthly production rate is slightly over 10. Toshiba Seiki has begun production of a modular spot welding high speed robot which can reach a monthly rate of 35-50. Toyoda Machine Works is also making an inexpensive building block system spot welding playback robot, but they will not be offered for public sale until the fall of 1982. Toyoda expects to sell 1,000 units annually. We do not know how many of these have already been shipped to Toyota. By 1983, Toyoda Machine Works and Toshiba Seiki, if they should be successful in their modular and simpler spot welding robots, could occupy a significant market share.

ARC WELDING

Arc welding operations are conducted in an extremely unfavorable environment where carbonic acid gas, fumes and heat are generated. As a result, arc welders must wear masks and consequently, must take time out frequently. Some loss of operating time is, therefore, inevitable. In addition, the new generation of young workers, being better educated, tend to shun arc welding. As a consequence, arc welding was particularly susceptible to robotics.

However, the large-sized robot such as the Kawasaki Unimate, which could handle heavy loads could hardly be justified economically by an application which largely used light weight welding guns. Yaskawa Electric Mfg., at present, dominates the arc welding robot applications with its relatively low-priced playback robot. Shinmeiwa developed arc welding robots for work on heavy plates while Osaka Transformer developed arc welding robots for work on sheets. Kobe Steel has produced a more expensive, continuous path control, arc welding robot. Hitachi had produced two robots suitable for arc welding: a sophisticated intelligent robot, and a low priced articulated playback robot. Matsushits has introduced a very competitive arc welding robot.

With Matsushita entering the arc welding area and with Hitachi capable of substantially increasing its output, it is entirely possible that these two firms will ultimately dominate the arc welding market.

SPRAY PAINTING AND COATING

Painting robots are the third largest type of playback robots and are now growing at the same rate as spot welding robots but not as fast as the arc welding robots. Spray painting and coating offer a rich area of application. To become skilled, a coating worker required 2-3 years of experience. However, the poor working environment and the tendency to a more educated society contributed to a developing skilled worker shortage. The necessity for a large percentage or rework made production planning difficult.

The industrial robot provided certain advantages in painting:

1) They insured stability of product quality and therefore made possible improved production planning and control. Despite the selection of the most skilled workman for finish coating, the quality of the finish varied according to the workers and the conditions of the day. In automobiles, the paint finish of a car, and especially its uniformity, is a determining element in the Japanese domestic consumer preference.

2) They made possible a multi-product mixed batch coating line.

3) They provided continuous production operation and reduced the need for intermediate stocks.

4) The manual workers and special purpose automatic coating machines tended to increase the use of paint to preclude uneven coating, especially in complicated shapes. In addition, special purpose automatic coating machines tend to overspray paint on smaller products in a multi-product coating line. In the case of spray painting an auto body, a savings of 10-20% in the use of paint has been effectuated. Reducing the amount of paint reduced the need for ventilation and therefore, saved on energy consumption.

5) Spray painting is a very unhealthy job because of the chemicals and dust. The spray painting robot could free the operator from staying in the spray booth. It provided a relatively simple way to meet safety regulations.

Kobe Steel introduced the Norwegian Trallfa spray painters--a rather expensive robot. Both Hitachi and Mitsubishi Heavy Industries worked with other firms--Nihon Parkerizing Co. and Iwata Air Compressor Mfg. Co. respectively to develop playback spray robots. Tokico offered a large variety of low priced painting robots while Nachi Fujikoshi offered a spray robot with both remote and direct teaching.

Considering the demand for spray robots (Nissan alone is reportedly seeking 300 units) it seems evident that production objectives will be increased. It is still too early to predict the future market share as changes are expected shortly, at least in Hitachi.

MACHINE LOADING AND UNLOADING

Industrial robots have been applied to a wide variety of production processes in which the basic breakdown of the process indicated that the robot is being used primarily, if not exclusively, for (1) loading and unloading, (2) trans-shipping and (3) palletizing and depalletizing. This refers to applications in the following areas:

1) die casting
2) forging
3) press work
4) plastic molding
5) machine tool loading
6) heat treatment

In each production process, fierce competition exists between those who designed industrial robots, often relatively unsophisticated, for particular production processes and the universal robot makers who offer playback and intelligent robots. In most cases, however, the specialists seem to have won out as of now. In press working operations Aida Engineering seems to have won dominance though strongly challenged by Toshiba Seiki. Similarly, Fujitsu Fanuc seems to enjoy supremacy now in the loading of machine tools, although Kawasaki H.I. has mounted a strong challenge.

In plastic molding (the automatic unloading of injection molded products) the small manufacturers dominate. Ichikoh Engineering Co. and Kyoshin Electric offer a complete line of fixed sequence machines. Star Seiki offers both fixed and variable sequence robots. Sailor Pen, likewise, offers relatively unsophisticated machines. For unloading workpieces from a die casting machine, Ichikoh offers its fixed sequence machine while Shoku and Daido offer variable sequence robots.

For putting workpieces into a furnace Shinko Electric has a relatively sophisticated variable sequence robot. Nachi Fujikoshi offers a specially designed robot to tolerate hot temperature which has been used to transfer workpieces from a furnace to a press.

In the forging area, a great number of robot makers offer a variety of specialized products: Aida, Kobe Steel, Komatsu and Nachi Fujikoshi.

MACHINING

In Japan one operator of NC machine tools serves on average less than two NC machine tools. This low ratio is the result of manual loading and unloading of the work pieces, manual disposal of chips and maintenance. Many Japanese firms sought robotic solutions to this problem. One of the consequences of the application of robots to machining besides improved productivity was improved production management. Robots could respond more elastically to changes in production volume and in the event of temporary requirements for increased production they could easily be worked overtime. Where the process was computerized, it was possible to know beforehand when a machinery operation would be completed.

While several other companies manufacture robots for machining Fujitsu Fanuc dominates this application area with an output of 100 units monthly. The Fanuc Model 0 uses the NC of the single machine tool which it services; the Model 1 and 2 (known in U.S. as 3) have their own NC and service up to two and five machines respectively. These machines make possible an unattended machining system that operates automatically at night.

The entry of Fujitsu Fanuc into robots has caused some of its competitors and some of the machine tool manufacturers to develop and produce robots of their own. This is especially true of Okuma which supplies its own NC for its machine tools. In addition, Yamatke-Honeywell and Ikegami Iron Works have started production of NC robots. Fanuc plans to introduce additional models in the summer of 1981.

Fanuc's competitors now are other manufacturers of robots who have modified their products to service machine tools.

TRANSFERRING

Closely allied to the machine loader/unloaders are the robots which are engaged primarily in the transfer of materials. Many robots equipped for specialized processes such as welding and painting can also be modified for transferring of materials. In addition, many conveyor equipment manufacturers were compelled to produce robots to compete with robot manufacturers entering their market. Some robot makers entered the materials handling market trying to carve a special niche for themselves.

Shinko Electric, Taiyo, and Kayaba Industry are manufacturers of machine loading robots that entered into the transfer field. The conveyor manufacturers that entered the field include Tsubakimoto and Sanki Engineering. The "universal robot makers" offering machines for transferring include Kawasaki, which offered modifications of its Unimate for that purpose, Daido Steel, Yaskawa, Nachi Fujikoshi and Toyoda Machine.

Some firms specifically developed a line of materials handling robots. Dainichi Kiko has developed a line of heavy duty transfer robots. Motoda (now Oriental Terminal Products) makes a complete line of what is described as multi-purpose versatile robots in both variable sequence and playback versions. Their major, if not exclusive, market, seems to be the materials handling area but Motoda claims that these robots can be used for welding and spray painting. Toyo Keiki has developed a series of variable sequence robots specifically dedicated to palletizing and depalletizing. The entire area of transfer robots like the area of machine loading robots is still too greatly splintered to provide a meaningful market share analysis.

ASSEMBLY ROBOTS

Assembly robots capable of inserting, screwdriving, bonding, and similar processes exist largely either in the R & D or the early application stage in Japan. Most major electrical manufacturers, such as Hitachi, Matsushita, Mitsubishi, NEC, Oki, and Fujitsu, have developed fully automatic systems for bonding. All these use cameras for visual perception to position by shape or pattern and in the case of Hitachi and Mitsubishi Electric, to detect defects. Fuji Electric's "Checker robot", which examines and rejects pharmaceutical pills is not a robot but does advance both visual (by use of a camera) and tactile perception for quality inspection.

In addition, special purpose automatic assemblers provided considerable data for constructing assembler robots. Hitachi built for Nissan an automatic tire fitting system which uses a machine hand to detect the hub bolts, position them, and tighten them. Hitachi also developed a fully automatic system for fitting rubber belts to tape recorders from which they learned assembly principles suitable for automobile and electric appliance belt fitting.

Hitachi manufacturers an intelligent robot with a 25 step memory capacity and a 200g. load capacity that can fit different components one by one in a specified order. The robot moves fast requiring only 1-2 seconds to fit workpieces. Its finger support is flexible to prevent excessive force. Its positioning precision does not have too close a tolerance but a special searching function automatically detects the holes of workpieces and fits them properly even when positioning is not accurate. An automatic rejecting function within the robot prevents assembly of defective workpieces.

Both Hitachi and Matsushita have built experimental robots to assemble electric vacuums.

The larger electronic/electrical manufacturing companies are planning to robotize 50-75% of their assembly operations by 1985. This would indicate that far more activity and experimentation has taken place than has so far been publicly revealed. (Still this forecast seems too optimistic to me.)

In March, 1981, Hitachi publicly announced a task force of 500 key technology experts to fashion and install a standardized assembly robot with both visual and tactile sensors, microcomputer control, and mobility and projected a 60% robotization of its assembly processes by 1985. In April, 1981, Matsushita announced a plan to marshall the entire staff of its technological division to develop intelligent industrial robots controlled by microprocessors and modularized (BBS). Matsushita revealed that some BBS robots were already functioning at its plants. The new robots were to be of three types (1) robots that position workpieces accurately, (2) robots that assemble workpieces, (3) robots that adjust the finished product to function as originally designed.

NEC then reported that it had developed a factory robot that assembles electronic machinery and appliance parts and components with a speed of 45 centimeters per second and a positioning accuracy of only 8 microns. The high precision and speed has been realized by computerization and by the application of the principle of electronic magnetic repellance, utilizing the linear-motor levitation technology that has been used by the Japanese National Railways in developing the "floating" train. The NEC linear-motor driven robot arm and hand picks up a machine part or component with a maximum load of 2 kilograms and carries it around by making it float over the work table. The high precision of movement is achieved by the robots's set of 16 sensors (visual) supported by a built-in microprocessor. NEC has been producing these assembly robots so far for its own factories and those of affiliated companies and in 1981 NEC plans to manufacture 50 units of these assembly robots.

In June, 1981, Ishikawajima Harima Heavy Industries, a close ally of Toshiba, announced plans to produce its Group Manipulator Module System (GMMS) with an articulated arm with the most advanced parallel circuit-type 16K RAMS in its microprocessor. In October, 1981, the GMMS will be tested (possibly at Toshiba?) and hopefully would be marketed by September, 1982 the latest.

Fujitsu Fanuc has also developed an assembly robot but no details are known except that it is being used at their new Fuji plant. Fujitsu is working closely on robot development with its affiliate.

The heavy emphasis on assembly and sense perception by both the private firms, universities, and public research institutes would seem to indicate the possibility of achieving the goal of popularization of assembly robots by 1985. As will be discussed later, the Japanese consider that the intelligent robot is an important element of export policy for the future.

BUILDING BLOCK SYSTEM (BBS)

The trend to incorporate various models into a single production line and to run these lines at higher speeds created some problems for the conventional universal type spot welding robot. In a mixed-flow production, line robot capacity was not fully and efficiently utilized. Furthermore, it required a large floor space for installation.

After a year of development and design and a half year of testing a new robot, the BBS became operational in May, 1978. The BBS is more compact in size and therefore, lower in cost than the conventional robot. It is a fully articulated multi-welding system wherein one control panel can control simultaneously up to 8 units (48 axes) and a hydraulic unit, separate from the robot's main body, controls three robots.

A study of two years of operation of the BBS welding in an auto plant indicated that its investment efficiency was 30% greater than a conventional robot system. The floor space required was reduced almost in half. The downtime of a BBS robot was one third of the downtime of a conventional robot.

BBS is the aim of most of the makers of sophisticated robots. How many of these building block systems are now operative in Japan is not known, but the several years of experience and the concentration of private research laboratories on the BBS would tend to substantiate the Japanese expectation of a substantial increase of the BBS far beyond application only to spot welding. Toyoda Machine Works and Toshiba Seiki have developed successful BBS robots but detailed production information for these companies and other BBS makers is currently unavailable.

FROM ASSEMBLY ROBOT TO FLEXIBLE MACHINE SYSTEM

The ultimate aim of the assembly robot is the creation of a comprehensive flexible manufacturing system (FMS) sometimes called the "unmanned factory". Such a system as exemplified by Fuji Electric's turnkey noodle factory would combine industrial robots with an automated warehouse, unmanned transport vehicles, belt conveyors, and computers which would simultaneously operate and record production.

Fujitsu Fanuc has invested ¥ 8 billion to create such as factory at Fuji to serve both as an automated manufacturer and a showroom. Its production capacity can be expressed in terms of monthly sales of ¥ 1.5 billion or in terms of production output--100 industrial robots, 150 electric discharge wire cutting machines, 100 numerical controls. The total number of employees is 100--19 machine processors, 63 assemblers, 4 inspectors, and 14 management and clerical personnel. A factory of this scale normally requires five times as many people.

The Japanese argue that the FMS actually results not only in reduced labor costs but reduced capital investment. Fuji operates 24 hours a day (unmanned at night) and equipment utilization ratios are close to the maximum. Furthermore, model changes can be made easily. With robots, machines need not be replaced or rebuilt; only the program must be changed. Prior to the introduction of industrial robots, factories often shut down for months to make the required alterations for a model change. In addition, a substantial amount of peripheral factory equipment such as lighting (the robots run at night in an unlighted plant),air conditioning and atmosphere control became unnecessary, at least in those areas where robots work without humans in proximity. Finally, the miniaturization of industrial robots, which is beginning to take place, will enable robots to be positioned very close to each other permitting a higher degree of efficiency in space utilization, a major element in Japan where industrial land is relatively scarce and high-priced. This plant contrasts sharply with the custom-made, almost handicraft assembly of many American robot manufacturers. The ability of Fanuc to increase its output swiftly is understandable; when they speak of an ultimate capacity of 360 units per month of industrial robots (which I presume includes both machine loading/unloading robots now being sold and their new assembly robots) it seems quite feasible.

FUTURE OF JAPAN'S INDUSTRIAL ROBOTS

The demand projections for rapid growth are based on the following analysis:

(1) The intelligent robot with an internal microcomputer and sensory perceptions has emerged and its field of application, especially in assembly and inspection, will widen and expand very rapidly. The announced plans of the major electrical manufacturers should provide substantial markets within each company and its affiliates.

(2) The shortage of skilled labor and the aging of the workforce will hasten the acceptance of industrial robots.

(3) The ability of industrial robots to work in adverse work environments resulting in savings on anti-pollution devices and energy will also accelerate acceptance of industrial robots.

(4) The government policies of financial aid and accelerated depreciation will encourage the use of industrial robots among the small and medium corporations. To the extent that such firms are suppliers of the larger process industries, they will be compelled to introduce industrial robots to provide swift on-time delivery of components, (the Komban System of Toyota).

(5) To increase Japan's competitiveness in international markets not only against the advanced Western nations, but also against its low labor cost competitors in East Asia (South Korea, Taiwan, Singapore, Hong Kong), Japanese firms are being compelled to automate.

(6) As demand for goods becomes less uniform and more diversified, small and medium batch multi-product production and constant modification will become predominant. The industrial robot, especially the BBS, has greater flexibility than the dedicated, single purpose automatic equipment.

(7) Japan has made robots a top priority both for research and production and an unrestrained effort is being made in that direction.

(8) The Japanese expect a substantial expansion of robots to areas

other than the process industries such as electrical and automobile manufacturing. In agriculture, robots will be used for crop dusting and spraying chemicals, harvesting fruit trees, tilling ground and even milking and feeding of cows. The Japanese expect robots to be used in many aspects of forestry.

A top priority has been given to underwater geological surveying and welding and machining (under 300 meters). Komatsu already has an underwater robot being used in bridge building. In mining, robots are being developed to work coal and ore faces. Robots are also being planned for building construction (especially multi-storied) and road construction. In the service industries robots are being developed to clean walls and floors of buildings, cleaning of boat hulls, cleaning electrical insulators in nuclear energy. The Japanese also expect to expand robot use in the hospital and the home. However, it should be emphasized that the top priority for the first half of the decade remains the intelligent robot for assembly.

(9) Japan expects to be a major exporter of industrial robots. This requires some additional comment.

The Japanese expect that Western Europe and the U.S., as well as Eastern Europe, will make strong efforts to increase worker productivity. These "reindustrialization" programs will necessarily involve increased use of industrial robots and Japan plans to export them. While exports of robots were less than 2% in 1980, the Japanese expect that in 1985 and 1990, exports will constitute about 20% of production.

The Japanese attitude is expressed in the following view of Machida of the Long Term Credit Bank: "The industrial robots presently in use are, technologically speaking, still in their infancy. During the 1980's they will mature from boyhood to the young adult stage. At present, Japan is the number one country qualified to be the parent of this child".

Accepting the challenge of Japan's lack of innovativeness and creativity, Machida wrote "It has been said that Japan cannot be victorious in the pioneer technology which is producing sophisticated, knowledge-intensive products because we do not possess high creativity. However, the expanding exports of Japanese intelligent robots will soon bear testimony to the fact of our international competitive strength, not only in improvement technology and application technology, but in pioneer technology as well".

Machida concludes his overview asserting that the "intelligent robot is representative of the leading edge of technology products" and that "the growth of the industrial robot industry will bear eloquent testimony to our strong international competitiveness even in the area of state-of-the-art technology". These views reflect the Japanese attitude of placing major stress on the export of intelligent robots as proof of Japan's creativity.

Returning to the estimated demand forecast, the most substantial growth through the eighties will be the intelligent robot. Playback and NC robots will grow at an accelerating rate in the first half of the decade, but should slow down in the second half. Variable sequence robots will also grow significantly in the first five years but level off in the second five years. The manual manipulators and fixed sequence machines show growth but their total share of output will decline significantly in value terms. Thus, in 1974, the sophisticated robots constituted 10.8% of total value; in 1980 26.4%, in 1985, 41%, and in 1990, 45%.

In terms of production, the two processes certain to grow throughout the decade will be assembly and inspection and measurement, probably at a rate of almost 40% annually. Spot welding, arc welding, and machine loading will continue to grow but at a decelerating rate. Spray painting should maintain continuous growth. In 1985 the production process for which robots are produced have been estimated as follows (in % of value).

1)	Assembly	21.7%
2)	Machine Tool Process	13.1
3)	Arc Welding	10.5
4)	Inspection	10.0
5)	Spot Welding	7.5
6)	Spray Painting	5.0
7)	Molding	3.3
8)	Others	28.9

How will the U.S. and Japan compare in the future? Using the U.S. definition of robots the following table includes the latest estimates.

TABLE 15

U.S.-Japan Comparison

Industrial Robots (U.S. Definition)

	Units		Value (million $)	
	U.S.	Japan	U.S.	Japan
1980	1,269	3,200	100.5	180
1985	5,195	31,900	441.2	2,150
1990	21,575	57,450	1,884.0	4,450

This is probably the best estimate of the future, assuming a continuation of those elements presently at work in each country. If we learn anything from history, it is that the future is never a simple continuation of the present. Therefore, hopefully the estimates remain "tentative and preliminary".

FOOTNOTE: While I alone am responsible for this report and its conclusions, many others provided assistance. In particular, Mr. Karl Kamita of Daiwa Securities ably researched and translated numerous articles on robotics in Japan. The works of Mr. Yonemoto of the JIRA, Mr. Machida of the Long Term Credit Bank of Japan, Prof. Ueda of Nagoya University, and Mr. Engelberger and Mr. Tanner, two "veterans" of U.S. robotics, not only added to my fund of knowledge but greatly influenced my thinking.

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INDUSTRIAL ROBOT TECHNOLOGY AND PRODUCTIVITY IMPROVEMENT

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Robots have received a great deal of publicity recently. The movie "Star Wars" and several television series such as "The Six Million Dollar Man" and "The Bionic Woman" have raised the consciousness of the public to the subject of robots. The enormous influx of foreign cars manufactured in part by robots has aroused awareness of the press and many politicians to the fact that robots can have a profound effect on industrial productivity. Many people today believe that the robot revolution is well under way, that factories are full of armies of highly intelligent robots, and that human workers are being displaced in droves. The facts are quite different.

First of all, there are only about 3000 robots installed in the entire country, secondly, the great majority of these are quite primitive, with no capacity to see or feel or respond to their environment in any significant way.

Most people think of a robot as an android, which walks and talks, sees and feels, and looks much like C3PO, or at least R2D2. Real robots are much more primitive. In its simplest form a robot is nothing more than a mechanical device that can be programmed to perform some useful act of manipulation or locomotion under automatic control. An industrial robot is a device that can be programmed to move some gripper or tool through space so as to accomplish a useful industrial task.

These robots are typically programmed by recording each task as a series of points in space. This recording is then simply replayed whenever the task is to be performed.

This simple procedure is adequate to perform a surprising number of industrial tasks, from spot welding automobile bodies, tending die casting machines, loading and unloading machine tools and presses, spray painting, and performing a wide variety of materials handling tasks.

Even arc welding can be performed by a robot which can neither see nor feel, so long as the parts to be welded are positioned in exactly the right place, and the welding parameters are controlled by some automatic system.

However, the great majority of industrial tasks are beyond the capacities of present day robot technology. Most tasks are too complex and unstructured, or involve too many uncertainties, or require too much ability to see and feel and adapt to changing circumstances. Before robots can significantly impact productivity of the economy as a whole, they must be used in hundreds of thousands and even millions of applictions. This will not be possible before a large number of technical problems are solved.

TECHNICAL PROBLEM AREAS

One of the first problems is accuracy. Robot positioning accuracy needs to be improved. Although the repeatability of most robots is on the order of 0.050 inch over its working volume (and in some cases as good as .005 inch), the absolute positioning accuracy may be off as much as 0.250 inch, or even 0.500 inch in some regions of the reach envelope. Thus, it is not possible to program a robot to go to an arbitrary mathematically defined point in a coordinate space and have any assurance that the robot will come closer than a half of an inch. This creates major problems in programming a robot from a computer terminal, or in transferring programs from one robot to another. Each robot must be taught its program separately by leading it point by point through its job, a tedious and costly task.

Presumably, this accuracy problem could be solved through closer robot manufacturing tolerances, although not without cost. Alternatively, calibration procedures such as illustrated in Figure 1, might allow each robot to offset its off-line program points to compensate for its mechanical inaccuracies. However, no efficient methods of robot calibration have yet been developed, and robot control software is not presently designed to use calibration tables for improving absolute positioning accuracy. Until this absolute position accuracy problem is solved, robot assembly in the small batch environment will be uneconomical. Teaching a robot every point in the trajectory of a complex assembly task is a time consuming job which may take many times longer than would be required to perform the same task by hand. Thus, using a robot for small lot batch assembly cannot be economical until software can be efficiently produced by off-line programming (i.e., programming from a computer terminal).

Second, dynamic performance must be improved. Present day robots are too slow and clumsy to effectively compete with human labor in assembly. Two possible exceptions to this are in arc welding where speed is governed by the welding process itself, and spot welding where the task corresponds to moving a heavy welding gun through a simple string of points in space -- a procedure which the robot is particularly adept at executing. However, if robots are to perform other types of assembly and construction tasks, they must be able to execute much more complex routines with much greater grace, dexterity, and speed than they are now capable of. Control systems need to be alternately stiff and compliant along different axes in space (which do not generally coincide with joint coordinates). This requires much more sophisticated cross-coupled servo control computations than are presently employed.

Furthermore, robot structures are typically quite massive and unwieldly. Most robots can lift only about one tenth of their own weight. Many cannot even do that. New mechanical designs using light weight materials such as carbon filament epoxies and hollow tubular construction are needed. Advanced control systems that can take advantage of such light weight structures and high speeds will be a major research project.

Much also remains to be done in gripper design. Typically, robot hands consist of pinch-jaw grippers with only one degree of freedom -- open and shut. Contrast this with the human hand which has five fingers, each with four degrees of freedom. No robot has come close to duplicating the dexterity of the human hand, and it is not likely that one will in this century. Certainly, dexterous hands with jointed fingers for industrial robots are a long way in the future. The problem is not so much in building such a mechanical structure, but in controlling it. No one has any idea how to design control algorithms to make use of such complexity and very little research is being done in this area.

Third, sensors of many different types must be developed. Robots must become able to see, feel, and sense the position of objects in a number of different ways. Processing of visual data must become faster and be able to determine 3-dimensional shapes and relationships. Robot grippers must become able to feel the presence of objects and sense the forces developed on those objects. Proximity sensors are needed on robot fingertips to enable the robot to measure the final few millimeters before contacting objects. Longer range proximity sensors are needed on the robot arm to avoid colliding with unexpected obstacles. Force and touch sensors are needed to detect and measure contact forces. A variety of acoustic, electromagnetic, optical, x-ray, and particle detectors are needed to sense the presence of various materials such as metals, ferromagnetics, plastics, fluids, and limp goods, and to detect various types of flaws in parts and assemblies. Both the sensing devices and the software for analyzing sensory data represent research and development problems of enormous magnitude.

Robot sensors is an area where there is much research activity. Robot vision is by far the most popular research topic, and also probably the most difficult. A computer must treat a visual image as an array of brightness dots called picture elements, or pixels. A typical scene may consist of from 16 thousand to over a million pixels. Interpretation of such a large volume of data is an enormous task even for a high speed computer. It often takes many seconds to several minutes to analyse a single picture by computer. This is far too slow for the robot to respond in a timely fashion to what it sees. Various tricks are used to speed up this response time. One is to illuminate the scene so that the objects appear as black and white silhouettes. Another is to assure that no two objects of interest touch or overlap. However, even under such artificial circumstances robot vision is a very complex problem and subject to many difficulties. Such techniques obviously limit the use of robot vision to a few select applications.

Other robot sensory inputs such as touch and force appear to be simpler in principle, but much less work has been done in these areas.

Fourth, control systems are needed which can take advantage of sophisticated sensory data from a large number of different types of sensors simultaneously. Present control systems are severely limited in their ability to modify a robot's behavior in response to sensed conditions. Robot control systems need to be able to accept feedback data at a variety of levels of abstraction and have control loops with a variety of loop delays and predictive intervals. See for example, Figure 2. Sensory data used in tight servo loops for high speed or high precision motions must be processed and introduced into the control system with delays of no more than a few milliseconds. Sensory data used for detecting the position and orientation of objects to be approached must be available within hundreds of milliseconds. Sensory data needed for recognizing the identity of objects or the relationship between groups of objects can take seconds. Control systems that are properly organized in a hierarchical fashion so that they can accommodate a variety of sensory delays of this type are not available on any commercial robot.

Fifth, robot control systems need to have much more sophisticated internal models of the environment in which they work. Future robot control systems will have data bases similar to those generated by Computer-Aided-Design (CAD) systems, and used for computer graphics displays. These can describe the three dimensional relationships of both the workplace and the workpieces. Such data bases are needed to generate expectations as to what parts should look like to the vision system, or what they should feel like to the touch sensors, or where hidden or occluded features are located. Eventually, such internal models might be used in the automatic generation of robot software; for example, by describing how a finished assembly should look, or even how each stage of an assembly or construction task should appear in sequence.

Sixth, techniques for developing robot software must be vastly improved. Programming-by-teaching is impractical for small lot production, especially for complex tasks where sensory interaction is involved. Shop floor personnel unskilled in computers must be able to instruct robots in what to do and what to look for in making sensory decisions. Eventually, it will be necessary to have a whole range of programming languages and debugging tools at each level of the sensory-control hierarchy. The development of compilers and interpreters and other software development tools, as well as techniques for making use of knowledge of the environment derived from a number of different sensors and CAD data-bases are research topics that will require hundreds of person-years of highly skilled systems software talent.

Seventh, interfaces need to be defined in some standardized way, so that large numbers of robots, machine tools, sensors, and control computers can be connected together in integrated systems. Trends in the field of computer-aided-manufacturing are toward distributed computing systems wherein a large number of computers, robots, and machine tools all interact and cooperate as an integrated system. This creates enormous software problems. Particularly in the case where sensors are used to detect variations in the environment and to modify the control output to compensate for those variations, the software can become extremely difficult to write and virtually impossible to debug. In order for such systems to work at all, it is necessary to partition the control problem into modular components and then develop interface standards by which the various system components can communicate with each other. See Figures 2 and 3.

It is often felt that standards are an inhibiting influence on a newly developing field -- that they impede innovation and stifle competition. In fact, just the opposite is true. Well chosen interface standards promote market competition, technology development, and technology transfer. They make it possible for many different manufacturers to produce various components of modular systems. Standard interfaces assure that multivendor systems will fit together and operate correctly. Individual modules can be optimized and upgraded without making the entire system obsolete. Interface standards also make it possible for automation to be introduced incrementally -- one module at a time. Systems can be made upward compatible and automated piecewise. Thus, users can test the automation waters gradually, without a large initial capital barrier.

Eighth, many potential robot applications require robot mobility. Most robots today are bolted to the floor or to a tabletop. Small robots can reach only one or two feet while larger ones can grasp objects nine or ten feet away. But many applications need robots which can maneuver over much larger distances. For example, a robot used to load a machine tool typically spends most of its time waiting for the machine tool to finish its operations. Sometimes a single robot can be positioned between two or more machine tools so that it can be more fully utilized. However, this leads to severe crowding of the work environment and in many cases is simply not practical. There are a few applications in which robots have been mounted on rails so that they can shuttle between several machines. Unfortunately, to date this has proven too expensive and cumbersome for wide scale use.

In many applications, particularly in arc welding of large structures like ships or buildings it is not practical to bring the work to the robot; the robot must go to the work, sometimes over distances of many tens of feet. One example is in the construction of large machinery such as road building equipment. Another example is in the building of ships. A good ship building robot would be able to maneuver inside odd shaped compartments, climb over ribs and bulkheads, scale the side of the ship's hull, and weld seams several hundred feet in length. Similar mobility requirements exist in the construction of buildings. Construction robots will need to be able to manuever through the cluttered environment of a building site. In some cases they will need to climb stairs, and work from scaffolding.

Robots will also be used in undersea exploration, drilling, and mining. Robot vehicles will someday explore the moon and planets. These applications will require significant new developments in mobility mechanisms.

Robot mobility in the factory using rails, carts, or overhead conveyors is a relatively simple problem that undoubtedly will be solved in the decade of the 1980's. Robot mobility on the construction site, under the sea, and in outer space however, is another issue entirely. The sensor, data processing, and control problems associated with these aspects of robot mobility will require years of concentrated research.

For the most part, these eight problem areas encompass profound scientific issues and engineering problems which will require much more research and development. It may be possible to improve the mechanical accuracy of robots, and to improve servo performance with little more than careful engineering. But much more fundamental research and development will be required before the sensor, control, internal modeling, software generation, systems interface, and mobility problems are solved. Much remains to be done in sensor technology to improve the performance, reliability, and cost effectiveness of all types of sensory transducers. Even more remains to be done in improving the speed and sophistication of sensory processing algorithms and special purpose hardware for recognizing features and analyzing patterns both in space and time. The computing power that is required for high speed processing of visual and acoustic patterns will even require new types of computer architecture.

Sensory-interactive control systems that can respond to various kinds of sensory data at many different levels of abstraction are still very much in the research phase. Current commercial robot control systems do not even allow real-time six-axis incremental movements in response to sensory data. None have convenient interfaces by which sensory data of many different kinds can be introduced into the servo loops on a millisecond time scale for true real-time sensory interaction. None of the commercial robot control systems have anything approximating CAD data bases or computer graphics models of the environment and workpieces. Finally, current programming techniques are time consuming and not capable of dealing with internal knowledge or sophisticated sensory interactions.

These are very complex problems that will require many person-years of research effort. It is thus not surprising that the robot applications are still extremely limited.

WHAT LIES IN THE FUTURE?

All of the problems listed above are amenable to solution. It is only a matter of time and expenditure of resources before sensors and control systems are developed that can produce dexterous, graceful, skilled behavior in robots. Eventually, robots will be able to store and recall knowledge about the world that will enable them to behave intelligently and even to show a measure of insight regarding the spatial and temporal relationships inherent in the workplace. High order languages, computer-aided-instruction, and sophisticated control systems will eventually make it possible to instruct robots using much the same vocabulary and syntax that one might use in talking to a skilled worker.

There is no question that given enough time and resources robotics will eventually become a significant factor in increasing productivity in industrial production. The question is: How much time and how many resources will be required before this becomes a reality?

In my opinion more than a few tens of millions, and less than a few hundreds of millions of dollars for research and development will be required to make robots capable of performing a sufficient number of tasks to make significant productivity improvements in industrial manufacturing. More than a few hundred and less than a few thousand person-years of high level scientific and engineering talent will be needed before robot software of sufficient complexity can be generated economically for small lot batch production. In other words, a national research and development effort of at least one, and perhaps two, orders of magnitude greater than what has been done to date will be required to produce a significant impact on industrial productivity. And more than just total dollars spent is important. Robotics research is systems research. At least a few stable, consistantly well funded research centers of excellence will be required.

The questions then are:

"How fast are we progressing along the road to the solutions?"
and
"Who are the researchers that are leading the way?"

In the United States there are four types of research laboratories:

1. University
2. Non-profit
3. Private Industry
4. Government

UNIVERSITY RESEARCH

Among the principal university labs are:

Stanford University: The robotics effort at Stanford is of long standing. Tom Binford has been doing pioneering work in three-dimensional vision for over a decade. His students have developed one of the most advanced robot programming languages available today called AL, for Arm Language. The Stanford artificial intelligence lab has produced a long list of ground breaking research projects in manipulation, hand-eye coordination, and robot assembly. Stanford is presently working on robot vision, a three-fingered hand, force sensing, robot programming languages, and geometric modeling for vision and programming. They also have a cooperative program with Unimation for robot mobility.

Stanford received about $200K in FY81 from NSF. There are about 14 graduate students working on various projects.

MIT has had a major robotics effort at least as long as Stanford. At present, Danny Hillis and John Hollerbach are building robot skin made of thin sheets of rubber lined with tiny wires that detect pressure. These are being used to give robots a sense of touch. MIT also is active in robot vision and programming languages. Tom Sheridan of MIT is working on Supervisory Control of Teleoperators. This work is currently directed toward undersea work and is partially funded by Naval Ocean Systems Center in San Diego. Total MIT funding is around one million per year. Office of Naval Research provides approximately 700K of this amount.

Carnegie-Mellon University has recently formed a Robotics Institute directed by Raj Reddy with funding from Westinghouse, ONR, DARPA and other industrial sponsors. The Institute has programs in flexible assembly, machining, sensory systems, vision, mobility and intelligent systems. In its less than two years of existence the Institute has recorded significant achievements in the expansion of sensory capabilities of machines, the integration of several machines into cells carrying out complex tasks, the application of vision and optics to a wide range of industrial tasks, the development of new robot mechanisms, and the application of artificial intelligence to the management of evolving intelligent technologies. Total funding is over $3 million, making it one of the best funded major university projects. Office of Naval Research contributes approximately 500K per year to Carnegie-Mellon University.

Rhode Island University has an impressive effort directed by John Birk on general methods to enable robots with vision to acquire, orient, and transport workpieces. The Rhode Island robot was the first to pick parts out of a bin of randomly oriented parts. Rhode Island is also doing work on dexterous robot grippers and robot programming languages. Funding from NSF is $210K per year and from industrial affiliates, about $750K per year.

University of Florida under Del Tessar is doing work in teleoperators, force feedback, and robot kinematics and dynamics. Funding from the Department of Energy, NSF, and State of Florida amounts to about $1 million per year.

Purdue University is doing research in robot control systems, robot programming, languages, machine vision, and modeling of part flow through industrial plants. Total NSF funding to Purdue is about $400K over a four year period.

A number of Universities have smaller robotics efforts, or efforts in related areas.

The University of Massachusetts is doing work in visual interpretation of natural scenes and design of parts for automatic assembly. ($125K per year) They have just received an NSF grant for $157K to study "Economic Applications of Assembly Robots".

University of Maryland Computer Vison lab under Azriel Rosenfeld is doing work on a number of image processing projects including robot vision and methods for using visual knowledge in interpreting images. (over $1 Million per year)

University of Rochester under Herb Voelcker is developing advanced methods of representing three dimensional shapes in a computer memory. The result of this work is a computer graphics language called PADL which is profoundly influencing the way future computer graphics systems are being designed. Much of this is being done with NSF funding. ($85,576 in FY81)

Rensselear Polytech Institute under Herb Freeman is also studying the generation of computer models for three-dimensional curved surface objects. ($98K)

University of Arizona is doing teleoperator work. ($113K)

University of Wisconsin is doing work in machine vision. ($60K)

Ohio State University under Robert McGhee is working on dynamics and control of industrial manipulators and legged locomotion systems. ($125K from NSF) DARPA has recently funded McGhee to build and test a man-carrying walking machine. This project is funded at $250K in FY81 and $630K in FY82. Battelle Labs are cooperating with Ohio State University in this effort.

University of Illinois, University of Pennsylvania, University of Washington, and the University of Texas all have small research projects in robotics, and robot related work.

Total National Science Foundation funding for university research in robotics and related fields is on the order of $5 million per year. Additional university funding from other sources such as industrial affiliates and internal university funding may run another $4 million per year. University research tends toward small projects of one or two professors and a few graduate students. The average NSF grant in robotics and related fields is around $150K per year.

Although support of university research by industry is on the rise, it is still small by European or Japanese standards. University efforts tend to be fragmented, progress is sporadic, and the issues addressed are often unrelated to the problems of industrial manufacturing.

NONPROFIT LABS

C. S. Draper Labs with Jim Nevins and Dan Whitney have been studying part-mating science and assembly system design for a number of years. They have performed a variety of assembly experiments, studied the use of force feedback, and developed a theory of the use of passive compliance in part-mating. Draper has also done economic modeling for designing industrial systems, and real-time simulation of the space shuttle remote manipulator system for NASA. NSF funding is about $200K per year. Draper also has a number of industrial clients for whom it performs design and construction of advanced assembly systems. Total funding is about $1 Million per year.

SRI International has an extensive robot research program that dates back to the SHAKEY Artificial Intelligence project that was funded by ARPA in the late 1960's. Presently SRI's program is headed by David Nitzan. Emphasis is on machine vision for inspection and recognition. Some very sophisticated robot vision research is being done on overlapping parts using structured light and a combination of binary and gray-scale vision. Work is also being done on printed-circuit board inspection, programmable assembly, vision-guided arc welding, and semiautomatic process planning. Funding from NSF is about $350K per year with about $350K per year from industrial affiliates. SRI was the first robotics lab to develop an industrial affiliates program. Office of Naval Research contributes approximately 250K for research in communication and negotiation between cooperating robots to distribute their workload. Additional $250K per year funding from NSF started in August 1981 for work on printed-circuit board inspection.

PRIVATE INDUSTRIAL RESEARCH LABS

General Motors has established a major robotics research effort at the G. M. Research Labs in Warren Michigan. They have concentrated on vision and have produced a new robot vision system called "CONSIGHT". This system has a unique method for obtaining silhouette images of parts on a conveyor belt that does not require back lighting and is not dependent on contrast between the part and the belt. General Motors is also interested in small parts assembly by robots and automatic inspection. Several years ago they contracted with Unimation to produce the PUMA robot; a small, accurate, computer controlled robot designed for assembly.

General Electric is becoming very active in robot research. G. E. has a substantial research effort in robot assembly, robot vision, robot controllers and new VLSI micro circuit technology. They have designed a very impressive laboratory robot which embodies a number of innovative concepts. G. E. also has a robot demonstration facility where they have one of almost every robot manufactured today. As a part of this facility they offer courses in robot programming and applications engineering. G. E. has also announced intentions of marketing the Italian PRAGMA robot in this country under the name of ALLEGRO, as well as the Hitachi Process Robot.

Westinghouse has established a productivity center in Pittsburgh with a robotics research lab containing 15 robots of all different kinds. This center supports Carnegie-Mellon University with $1 million per year grant for manufacturing research. Westinghouse also has a cost sharing project with NSF called APAS for Adaptable Programmable Assembly System. This research project will be complete in 1982. It has been funded by NSF at about $500K per year. Westinghouse also has a R&D center which is working with the University of Florida to assess what teleoperator technology is needed for nuclear power plants.

IBM has been involved in robotics research for a number of years. IBM has developed robot programming languages called AUTOPASS and EMILY and has studied the problem of robot assembly. IBM has also developed its own robot which it uses in its own manufacturing operations. All of the IBM robotics effort is internally funded and details of the projects are not available.

Texas Instruments also has developed a robot which they use for assembly and testing of hand calculators. No details of this effort are available.

Martin-Marietta has a robotics effort directed primarily toward NASA and DOD interests. They are working on automated diagnosis and checkout of avionics, cockpit simplification, and various autonomous devices. Martin is also studying the speed requirements for space shuttle manipulators, coordinate transformations, and two arm coordination. Funding is about $3 million per year.

Automatix is a small new company with a heavy emphasis on robotics research. Robot vision, microcomputer control systems, and applications engineering in arc welding systems are their main target areas.

Machine Intelligence Corporation is another small company, whose technical staff includes the principals who pioneered robot vision at SRI International. Machine Intelligence Corporation manufactures computer vision systems to be incorporated into turnkey inspection, material-handling and assembly systems. In cooperation with Unimation Corporation, they have developed the Univision system, the first commercially-available "seeing" robot, marrying an advanced vision system with the PUMA robot, programmable under a special language "VAL". They have an NSF Small Business Inovnovation grant for research on a method of person/robot communication, to permit programming a robot without need for a professional programmer.

ROBOT MANUFACTURERS

The major robot manufacturers, of course, also conduct a substantial amount of research. Unimation is working on advanced control systems, calibration techniques, mobility systems, and programming techniques.

Cincinnati Milicron has a research group working on new control system architectures, programming languages, and mechanical design.

Prab-Versatran, Autoplace, Advanced Robotics, Devilbiss, Mobot, Nordson, Thermwood, ASEA, KUKA, Tralfa, U. S. Robots, and perhaps ten other small new robot companies are all aggressively developing new and improved product lines.

The level of funding for research by the robot manufacturers is proprietary. However, based on the aggregate sales of about $150 million for the entire U. S. robot industry, it is probably around $15 million per year and scattered over about twenty companies. One or two of the largest manufacturers are spending around $5 Million per year on research. However, it is doubtful if more than three manufacturers are spending more than $1 million per year.

GOVERNMENT RESEARCH

The National Bureau of Standards is pursuing research related to interface standards, performance measures, and programming language standards for robot systems and integrated computer-aided-manufacturing systems. This work focuses on advanced concepts for sensory-interactive control systems, modular distributed systems, interfaces between modules, and sensor interfaces to the control systems of robots and machine tools. Funding from the Department of Commerce is about $1.5 million per year.

The Air Force Integrated Computer Aided Manufacturing (ICAM) project has funded several robot development and implementatiion projects. A contract with General Dynamics introduced robots into drilling and routing applications in aircraft manufacturing. A contract with McDonnell-Douglas resulted in a robot programming language based on the APT N/C tool language. A contract with Lockheed Georgia produced a study of potential future aerospace applications for robots. Total funding was about $1 million per year. This work is now completed. Technical Modernization, a related program is presently funding General Dynamics to design several aspects of an automated factory. Funding for this is about $4 million per year. Total ICAM funding is $17 million per year for computer based information, planning and control, and systems engineering methodologies for increased automation. Estimated future ICAM funding for robotics is $2 million per year.

NASA has a number of small robotics projects at several of its centers. JPL has a project in stereo vision, force feedback grippers, and the use of automatic planning programs for mission sequencing applications. Langley Research Center is doing research on robot servicing of spacecraft. Marshall Space Flight Center has developed a prototype robot arm for satellite refurbishing and is working on free-flying teleoperators. Johnson Space Center is managing the development of the space shuttle remote manipulator system. The total NASA reseach budget for automation is about $2 million.

The Naval Air Rework Facility in San Diego is funding the development of robots to remove rivets and fasteners from airplane wings, to strip and repaint aircraft, and to perform wire assembly. Total funding for these three projects is about $3 million per year.

The Naval Ocean Systems Center is currently exploring various military applications of robot and teleoperator systems. There are specific interests in teleoperated and robot submersibles, teleoperated and robot land vehicles, teleoperated lighter than air vehicles, underwater manipulators, stereo optic and acoustic vision, remote presence, autonomous robot knowledge representation and decision making and complex robot system specification and verification. These interests are distributed among six projects funded at a total of $650K per year.

The total government funding for robotics is about $10 million per year.

OVERSEAS RESEARCH

Overseas robotics efforts are considerably better funded.

Although exact figures are hard to obtain, most knowledgeable observers estimate that the Japanese are spending from three to ten times as much as the United States on robotics and related research. The Western Europeans are estimated to be spending from two to four times as much as the U. S. Certainly the corporate giants of Europe and Japan are heavily involved. Fiat, Renault, Olivetti, and Volkswagon have all developed their own robots, and many other European firms are marketing a wide variety of very sophisticated robots. In Japan, Kawasaki, Hitachi, Yasakawa, Fanuc, and Misubitshi all have major research laboratories and are aggressively marketing a wide variety of industrial robots. Fanuc has teamed up with Siemens of Germany to market a very competitive line of robots under the name General Numeric.

European and Japanese university efforts are heavily subsidized by the respective governments and university-industry collaboration is very close. Many university research laboratories are elaborately equipped with the most modern N/C machine tools and the best robots. Many of these machines are donated by private industry. Government support for salaries and overhead makes it possible for the universities in Europe and Japan to sustain large and coherent research programs. Even if the total U. S. effort were equivalent, the lack of U. S. centers of excellence supported on a consistent long term basis would put the U. S. at a serious disadvantage. The fact is, U. S. robotics research efforts are neither better funded nor better organized than those of our overseas trading partners. The Japanese have made the development of the automatic factory a high priority item of national policy. European research is heavily subsidized by the government funds. In both places robotics technology is treated as crucial to national economic development.

IMPLEMENTATION

In the United States at present, there are only about 3000 robots installed. That's less than the number of workers employed in a single factory in many companies. That's less than the graduating class of some high schools in this country. Today, there is a bigger market for toy robots than for real robots. So at least for the present, robots are having almost no effect one way or another on overall productivity in this country. Today, robots are being produced in the United States at the rate of about 1500 per year. Predictions are that this will probably grow to between 20,000 and 60,000 robots per year by the year 1990. In other words the production rate is growing at about a factor of 10 to 30 per decade. At that rate the U. S. will be lucky to have a million robots in operation before the year 2000. This means that unless there is some drastic change in the presently projected trends, there won't be enough robots in operation to have a significant impact on the overall productivity of the nation's economy before the turn of the century.

Of course, there will be some specific areas where the impact of robots will be large. In areas like automobile spot-welding, robots have already had some effect. By the mid 1980's there may be a significant effect on productivity in arc welding.

Arc welding is a hot, dirty, unpleasant job where the welder must wear heavy protective clothing and must work in the presence of a shower of hot sparks and choking smoke. Typically a human welder cannot keep his torch on the work more than 30% of the time. A robot welder, on the other hand can keep its torch on the work about 90% of the time. Thus, even though the robot cannot weld any faster than a human, it can turn out about 3 times as much work.

Unfortunately, present day robots cannot set up their own work. That requires a human assistant. So this reduces the productivity advantage. Also, the robot must be programmed to perform the welding task. Typically this takes much longer than would be required to actually perform a weld. Thus, unless the robot is used to perform many repetitions of the same welding task there is no productivity gain.

Of course, once robots become intelligent enough to assemble and set up their own work, productivity will improve. Once robots become clever enough to look at the job and figure out where to put the weld, productivity will improve even more. Eventually, welding robots will be sufficiently sophisticated to work from plans stored in computer memory and to correct errors which may occur during a job. Welding robots will then be able to work nights and weekends (four shifts per week) completely without human supervision. At that point productivity improvements over present methods of many hundreds of percent become possible. Unfortunately, we are a long way from that today. There are many difficult research and development problems that must be solved first. Unless the level of effort in software development is increased many fold, these improvements will not be realized for many years.

Let's look at another industry, the metal cutting industry, where robots are already being used to load and unload machine tools. This is a relatively simple task, so long as the parts are presented to the robot in a known position and orientation. During the 1980's, robot sensory and control capabilities will improve to the point where robots can find and load unoriented parts, or in some cases, even pick parts out of a bin filled with randomly oriented parts lying on top of each other. This may improve productivity by hundreds of percent because it will make it possible to install robots in many exisiting plants without major re-engineering of production methods. For example, in conventional N/C machine shops a single machinist could set up several machines which could then run for extended periods unattended. In some cases robot tended machines may run overnight and on weekends without human intervention.

By 1990 robots may begin to have a significant impact on mechanical assembly. There has been a great deal of research effort spent on robot assembly. Unfortunately, the results have not been spectacular--yet. On the one hand, robots cannot compete with classical so-called "hard automation" in assembly of mass produced parts. General purpose machines like robots are still too slow and too expensive to be economical for mass production assembly tasks. On the other hand, robots cannot yet compete with human assembly workers in small lot assembly. Humans are incredibly adaptable, dexterous, as well as fast, skilled, and relatively cheap compared to robots. A human has two hands and ten fingers with arms, and shoulders mounted on a mobile platform equipped with a total of 56 degrees of freedom. The human has a fantastically sophisticated vision system and can be programmed to perform a wide variety of tasks quite easily. Even in a relatively routine task such as the assembly of an automobile alternator (performed at the C. S. Draper Lab, Cambridge, MA), test results indicated that robot assembly would be only marginally effective economically even after every phase of the task had been optimized.

Nevertheless, progress is being made and will continue. Robot capabilities will gradually increase. Sensory systems will become more sophisticated and less expensive. The cost of computing hardware is dropping rapidly and steadily with no sign of bottoming out. Software costs are likely to be the major impediment to robot development for the foreseeable future, but even these are slowly yielding to the techniques of structured programming and high level languages.

Eventually, extremely fast, accurate, dexterous robots will be programmed using design graphics data bases which describe the shape of the parts to be made and the configuration of the assemblies to be constructed. Eventually, robots will be able to respond to a wide variety of sensory cues, to learn by experience and to acquire skills by self optimization. Such skills can then be transferred to other robots so that learning can be propagated rapidly throughout the robot labor force.

During the 1990's robots will probably enter the construction trades. Under the tutelage of a human mastercraftsman, apprentice robots will carry building materials, lift and position wall and floor panels, cut boards to size, and lay brick, block, and eventually stone. In the next century, labor intensive building techniques (using robot labor) may once again become practical. Homes, streets, bridges, gardens and fountains may be constructed of sculpted stone, quarried, cut, and assembled by robots. Eventually, robots will mine the seabed, and farm the surfaces of the oceans for food and fuel And, of course, robots will play a major role in outer space, -- in the construction of large space structures, in space manufacturing, and in planetary exploration.

Sometime, perhaps around the turn of the century, robot technology will develop to the degree necessary to produce the totally automated factory. In such factories robots will perform most, if not all, of the operations that now require human skills. There will be totally automatic inventory and tool management, automatic machining, assembly, finishing, and inspection systems. Automatic factories will even be able to reproduce themselves. That is, automatic factories will make the components for other automatic factories.

Once this occurs, productivity improvements will propagate from generation to generation. Each generation of machines will produce machines less expensive and more sophisticated than themselves. This will bring about an exponential decline in the cost of robots and automatic factories which may equal the cost/performance record of the computer industry. For the past 30 years computing costs have spiraled downward by 20% per year. This, at least in part, is due to the fact that computers are used to design, construct, and test other computers. Once automatic factories begin to manufacture the components for automatic factories, the cost of manufacturing equipment will also fall exponentially. This, obviously, will reduce the cost of goods produced in the automatic factories. Eventually, products produced in automatic factories may cost only slightly more than the raw materials and energy from which they are made.

The long range potential of totally automated manufacturing is literally beyond our capacity to predict. It may change every aspect of industrial society. Automatic factories that can operate without human labor, and reproduce themselves, could lead to an entirely new era in the history of civilization.

Now, in the light of the unprecedented economic potential of robots, I suppose I should comment on why the implementation of this technology is proceeding so slowly.

First, at least in the U.S., funding for robotics R&D has been very modest. Every indication is that in the future, support will grow, but not dramatically. Certainly, there is nothing to suggest that a crash development program on the scale of the Manhattan Project or the Apollo Moon Program is imminent. Certainly, there are no plans for the federal government to launch such an effort and private investment funds are not likely to be committed on a massive scale because of the long time to pay back. Robotics is still a long term research topic. We are a long, long way from a sophisticated sensory interactive, intelligent, highly skilled, dexterous, economically feasible, and commercially manufacturable robot. Research in this area is long term, time consuming, and risky. Also, there is no certainty that inventions can be kept proprietary. There is therefore, no guarantee that the firms which make the investments can capture enough of the benefits to make the risk worthwhile.

Secondly, even after the research and development problems are solved, several decades and many hundreds of billions of dollars will be required to convert the present industrial base to robot technology. This enormous investment will severely tax available sources of capital. The transformation of the entire industrial plant of a country simply cannot be achieved except over an extended time period.

Thirdly, and perhaps most importantly, many voters question the desirability of rapid, massive deployment of robot technology. Despite the obvious benefits from productivity improvement, there would be serious social and economic adjustments necessary as a result of such a rapid productivity growth. Productivity improvement by its very nature reduces the amount of human labor needed to produce a given product. Thus, an obvious, but I believe incorrect conclusion is that a rapid increase in productivity would lead to unemployment. There is a wide spread perception that robots pose a threat to jobs. The fear is that if robots were introduced at the rate that is technologically possible, unemployment would become a serious problem.

However, widespread unemployment is not the inevitable result of rapid productivity growth. There is not a fixed amount of work! More work can always be created. All that is needed is a way to meet the payroll. Markets are not saturated. The purchasing power of consumers can always be increased at the same rate that more products flow out of the robot factories. At present, there is plenty of demand. The mere fact of inflation is prima facie evidence that consumer demand exceeds the ability of present production techniques and facilities to supply goods and services at constant prices. Work is easy to create. So is demand. What is hard to produce is goods and services that can be sold for a profit, at, (or below) the current market price.

Nevertheless, the average citizen is unconvinced that advanced automation would necessarily put increased spending power into his or her pocketbook. The question is -- If the robots have most of the jobs, how will average people get their income? In order for most people to be convinced that robots are going to bring more benefits than problems it will be necessary to demonstrate that a variety of alternative income producing occupations will be created to fill the void left by those jobs which are taken over by robots. Fortunately, this is not difficlt to do.

Perhaps, the most obvious source of new jobs is in the industries which must be created in order to convert to a robot based economy. Certainly if robots are to be manufactured in large enough quantities to make a significant impact on the existing industrial system, entirely new robot manufacturing, sales, and service industries will emerge and millions of exciting new jobs will be created. A typical industrial robot costs from $30,000 to $80,000 and sometimes more by the time it is installed and operating. This means that every robot installed creates from 2 to 4 person-years of work somewhere in the economy. The robot market is presently growing at about 35% per year, which means it doubles about every 3 years. As long as this growth rate continues, robot production will add jobs to the economy about as fast as robot installation takes them away.

It will be many years, perhaps many decades, before robots can design, manufacture, market, install, program, and repair themselves with little or no human intervention. In the meantime, the manufacture and servicing of robots will produce an enormous demand for mechanical engineers, technicians, computer programmers, electronic designers, robot installation and repair persons. New robot companies will require secretaries, sales persons, accountants, and business managers. It seems likely that the robot industry will eventually employ at least as many people as the computer and automobile industries do today.

Converting the world's existing industrial plants from manual to robot labor will require many decades and will cost as much as the total existing stock of industrial wealth. This is a Herculean task which will provide employment to millions of workers for several generations. For a country like the United States which has a strong technological base, the world market in robots could easily create twice as many jobs in robot production as were lost to robot labor. Needless to say, the export of robot systems (as well as products made by them) could have a strong positive effect on the balance of trade and the strength of the dollar on the international market.

In general, industries that use the most efficient production techniques grow and prosper, and hire more workers. Markets for their products expand and they diversify into new product lines. Workers displaced by automation are simply transferred into new growth areas or retrained for different occupations. It is in the industries that fall behind in productivity that job layoffs are prevalent. Inefficient industries lose market-share to competitors, shrink, and eventually die. Thus, the biggest threat to jobs is not in industries that adopt the latest robot technology, but in those which do not.

For example, there are almost one-half million jobless workers today in the American automobile industry. This is not because of a couple thousand robots. It is because of the energy crisis and because of foreign competition. U. S. auto workers are suffering unemployment more because of robots in Japan than because of robots in Detroit. If America continues the present low rate of productivity growth, we cannot help but have even greater unemployment. Foreign trading partners are modernizing at a rapid rate. If we do not innovate, our products cannot compete, and our workers will find their jobs being taken away by foreign competition.

Improving productivity is not easy. It requires research, development, education, capital investment, and incentives to do better. The new technology of advanced automation is not a quick fix. It is a long range solution. Robots have much promise but a long way to go. We are only beginning to understand some of the technical problems. We are many years, perhaps several decades from making truly intelligent, highly skilled robots. But technical solutions will come. It is only a matter of time, money, and intellectual resources. The real question is whether we can evolve a society in which robots will complement, not compete with, humans for their livelihood. If this problem can be solved, then the prospects for the future may be very bright indeed. Robots and automatic factories have the potential to increase productivity virtually without limit. This potential, if brought to reality, could create a material abundance and standard of living which far exceeds the horizon of today's expectations. Over the next two centuries the technology of robotics and advanced automation could make everyone rich. Robots someday could provide the economic foundation for an "everypersons' aristocracy." However, this will require that we find a way to make them work for us, and not in competition with us. To protect the human worker's livelihood in the coming decades there are several steps which can and should be taken.

First, we must provide retraining for workers displaced by robots for new and better occupations.

Second, (after a decade or so when robots begin to make a significant impact on productivity) we can decrease the workweek. It is nowhere written in stone that humans must work 40 hours per week. As robots take over more and more work, humans can improve their work environment and decrease their work periods to 30, 20, or even 10 hours per week. Education and leisure activities can be increased virtually without limit. Eventually, all "work" could be voluntary.

However, in order to achieve this we will need to explore a wide variety of mechanisms for broadening our ownership of robots and automatic factories. Employee stock ownership plans, individual robot-owner entrepreneurs, and even semi-public mutual fund ownership plans might be developed in the future. If everyone could own the equivalent of one or two robots, everyone would be financially independent, regardless of whether they were employed or not.

Finally, in the next few years and decades, we must recognize that it is premature to worry about insufficient work to go around. There is virtually an unlimited amount of work that needs to be done in eliminating poverty, hunger, and disease, not only in America, but throughout the world. We need to develop renewable energy resources, clean up the environment, rebuild our cities, exploit the oceans, explore the planets, and colonize outer space. The new age of robotics will open many new possibilities. What we humans can do in the future is limited only by our imagination to see the opportunities and our courage to act out our beliefs.

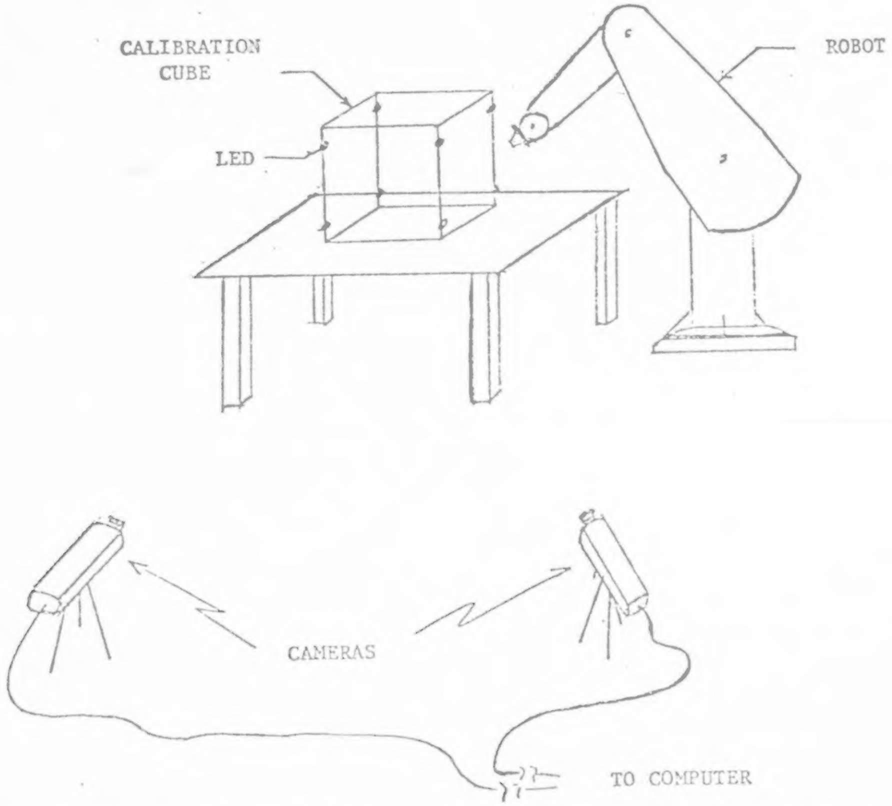


Figure 1. Remote, in situ robot trajectory calibration system. Each of the two cameras can measure the x and y position of light-emitting-diodes (LEDs). Initially, a calibration cube with a set of LEDs at known points is used to compute the positions and viewing angles of the two cameras. Then the two cameras can track a LED on the robot so as to determine the 3-dimensional position accuracy of the robot over its working volume.

Explanation of Figure 2.

The command and control structure for successful organizations of great complexity is invariably hierarchical, wherein goals, or tasks, selected at the highest level are decomposed into sequences of subtasks which are passed to one or more operational units at the next lower level in the hierarchy. Each of these lower level units decomposes its input command in the context of feedback information obtained from other units at the same or lower levels, or from the external environment, and issues sequences of subsubtasks to a set of subordinates at the next lower level. This same procedure is repeated at each successive hierarchical level until at the bottom of the hierarchy there is generated a set of sequences of primitive actions which drive individual actuators such as motors, servo valves, hydraulic pistons, or individual muscles. This basic scheme can be seen in the organizational hierarchy on the left of Figure 2.

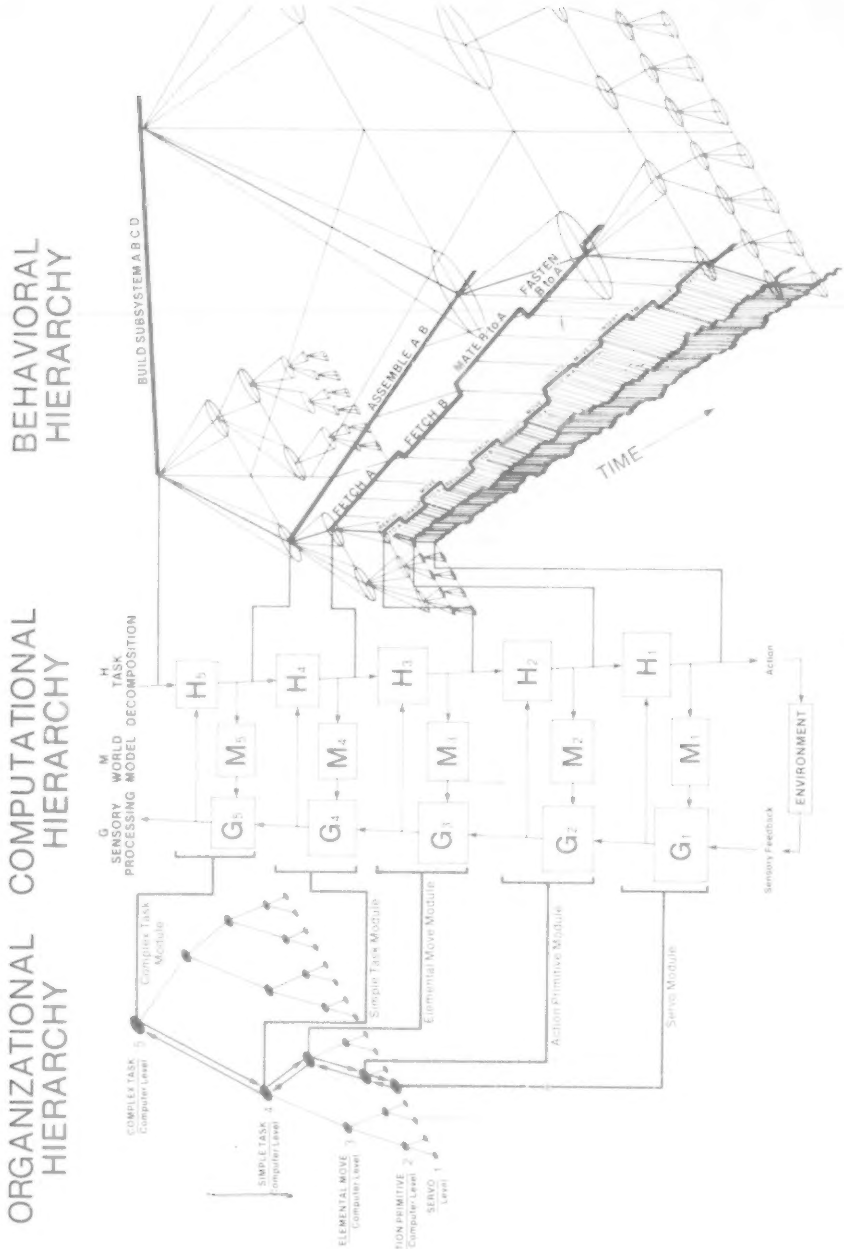
A single chain of command through the organizational hierarchy on the left is shown as the computational hierarchy in the center of Figure 2. This computational hierarchy consists of three parallel hierarchies: a task decomposition hierarchy, a sensory processing hierarchy, and a world model hierarchy. The sensory processing hierarchy consists of a series of computational units, each of which extract the particular features and information patterns needed by the task decomposition unit at that level. Feedback from the sensory processing hierarchy enters each level of the task decomposition hierarchy. This feedback information comes from the same or lower levels of the hierarchy or from the external environment. It is used by the modules in the task decomposition hierarchy to sequence their outputs and to modify their decomposition function so as to accomplish the higher level goal in spite of perturbations and unexpected events in the environment.

The world model hierarchy consists of a set of knowledge bases that generate expectations against which the sensory processing modules can compare the observed sensory data stream. Expectations are based on stored information which is accessed by the task being executed at any particular time. The sensory processing units can use this information to select the particular processing algorithms that are appropriate to the expected sensory data and can inform the task decomposition units of whatever differences, or errors, exist between the observed and expected data. The task decomposition unit can then respond, either by altering the action so as to bring the observed sensory data into correspondence with the expectation, or by altering the input to the world model so as to bring the expectation into correspondence with the observation.

Each computational unit in the task decomposition, sensory processing, and world modeling hierarchies can be represented as a finite-state machine. At each time increment, each unit reads its input and based on its present internal state computes an output with a very short time delay.

If the output of each unit in the task decomposition hierarchy is described as a vector, and plotted versus time in a vector space, a behavioral hierarchy such as is shown on the right side of Figure 2 results. In this illustration a high level goal, or task, (BUILD SUBASSEMBLY ABCD) is input to the highest level in a robot control hierarchy. The H5 task decomposition unit breaks this task down into a series of subtasks, of which (ASSEMBLE AB) is the first. This "complex" subtask command is then sent to the H4 task decomposition unit. H4 decomposes this "complex" subtask into a sequence of "simple" subtasks (FETCH A), (FETCH B), (MATE B to A), FASTEN B to A). The H3 unit, subsequently decomposes each of the "simple" subtasks into a string of "elemental moves" of the form (REACH TO A), (GRASP), (MOVE to X), (REALEASE), etc. The H2 decomposition unit then computes a string of trajectory segments in a coordinate system fixed in the work space, or in the robot hand, or in the work piece itself. These trajectory segments may include acceleration, velocity, and deceleration profiles for the robot motion. In H1, each of these trajectory segments are transformed into joint angle movements and the joint actuators are servoed to execute the commanded motions.

At each level, the G units select the appropriate feedback information needed by the H modules in the task decomposition hierarchy. The M units generate predictions, or expected values, of the sensory data based on the stored knowledge about the environment in the context of the task being executed.


ORGANIZATIONAL HIERARCHY
COMPUTATIONAL HIERARCHY
BEHAVIORAL HIERARCHY
COMPLEX TASK Computer Level 5
SIMPLE TASK Computer Level 4
ELEMENTAL MOVE Computer Level 3
ACTION PRIMITIVE Computer Level 2
SERVO Level 1
Complex Task Module
Simple Task Module
Elemental Move Module
Action Primitive Module
Servo Module
G SENSORY PROCESSING
M WORLD MODEL
H TASK DECOMPOSITION
G5
M5
H5
G4
M4
H4
G3
M3
H3
G2
M2
H2
G1
M1
H1
Sensory Feedback
ENVIRONMENT
Action
BUILD SUBSYSTEM A B C D
ASSEMBLE A B
FETCH A
FETCH B
MATE B to A
FASTEN B to A
TIME

Explanation of Figure 3.

The computing architecture shown in Figure 3 is intended as a generic system that can be applied to a wide variety of automatic manufacturing facilities and can be extended to much larger applications. The basic structure is hierarchical, with the computational load distributed evenly over the various computational units at the various different levels of the hierarchy. At the lowest level in this hierarchy are the individual robots, N/C machining centers, smart sensors, robot carts, conveyors, and automatic storage systems, each of which may have its own internal hierarchical control system. These individual machines are organized into work stations under the control of a work station control unit. Several work station control units are organized under, and receive input commands from a cell control unit. Several cell control units may be organized under and receive input commands from a shop control unit, etc. This hierarchical structure can be extended to as many levels with as many modules per level as are necessary, depending on the complexity of the factory.

On the right side of Figure 3 is shown a data base which contains the part programs for the machine tools, the part handling programs for the robots, the materials requirements, dimensions, and tolerances derived from the part design data base, and the algorithms and process plans required for routing, scheduling, tooling, and fixturing. This data is generated by a Computer-Aided-Design (CAD) system and a Computer-Aided-Process-Planning (CAPP) system. This data base is hierarchically structured so that the information required at the different hierarchical levels is readily available when needed.

On the left is a second data base which contains the current status of the factory. Each part in process in the factory has a file in this data base which contains information as to what is the position and orientation of that part, its stage of completion, the batch of parts that it is with, and quality control information. This data base is also hierarchically structured. At the lowest level, the position of each part is referenced to a particular tray or table top. At the next higher level, the work station, the position of each part refers to which tray the part is in. At the cell level, position refers to which work station the part is in. The feedback processors on the left scan each level of the data base and extract the information of interest to the next higher level. A management information system makes it possible to query this data base at any level and determine the status of any part or job in the shop. It can also set or alter priorities on various jobs.

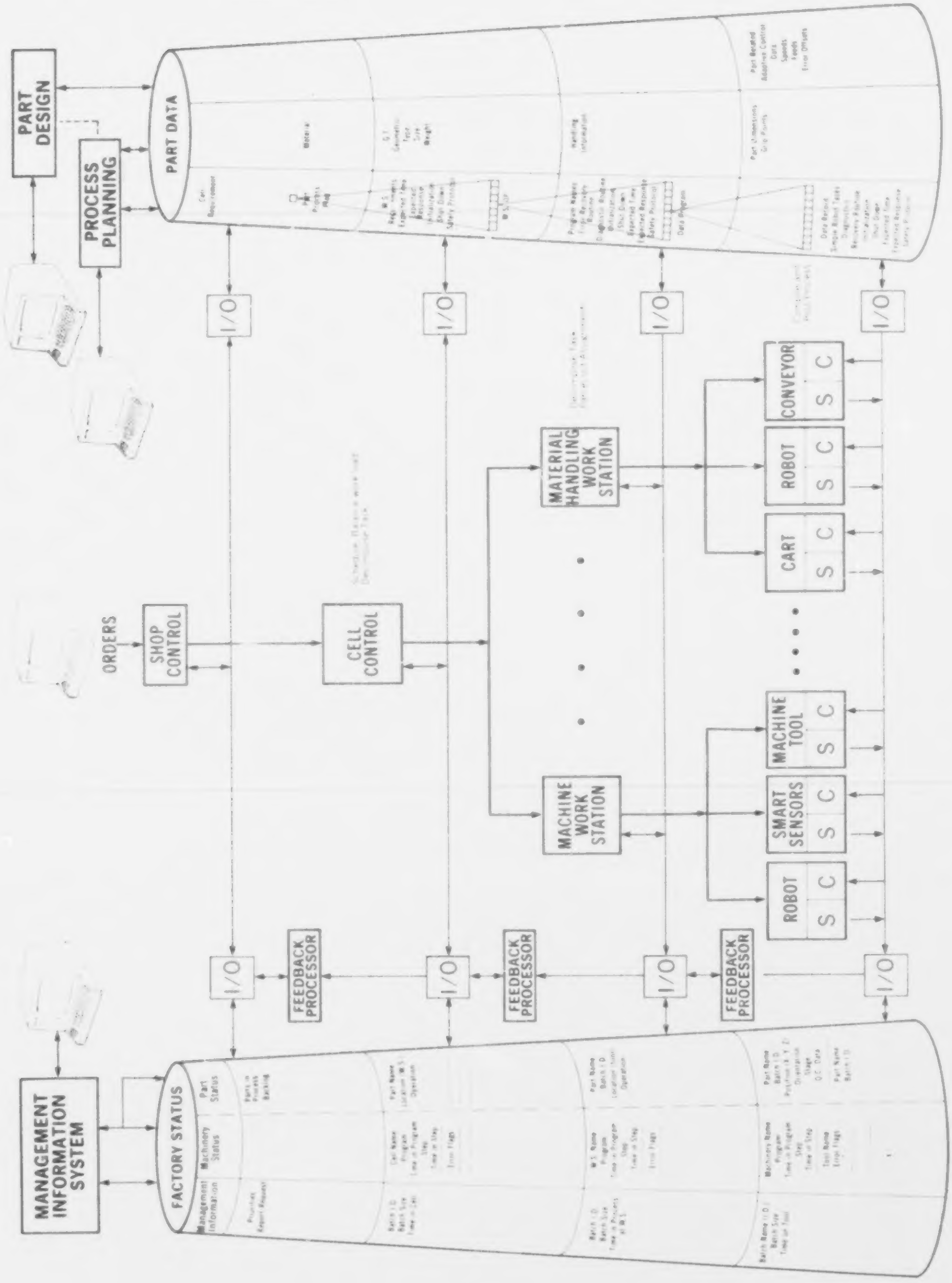

MANAGEMENT INFORMATION SYSTEM
FACTORY STATUS
Management Information
Machinery Status
Part Status
FEEDBACK PROCESSOR
FEEDBACK PROCESSOR
FEEDBACK PROCESSOR
I/O
ORDERS
SHOP CONTROL
CELL CONTROL
MACHINE WORK STATION
MATERIAL HANDLING WORK STATION
ROBOT
SMART SENSORS
MACHINE TOOL
CART
ROBOT
CONVEYOR
S
C
PROCESS PLANNING
PART DESIGN
PART DATA
Cell Requirement
Material
Part Dimensions Grip Points

Figure 3

CASE WESTERN RESERVE UNIVERSITY

RESEARCH PROGRAM IN INDUSTRIAL ECONOMICS

Working Paper No. 108A

ROBOTICS, PROGRAMMABLE AUTOMATION AND IMPROVING COMPETITIVENESS*

Bela Gold**

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* Prepared for the Robotics Workshop of the Congressional Office of Technology Assessment held in Washington, D. C. on July 31, 1981.

** William E. Umstattd Professor of Industrial Economics and Director of the Research Program in Industrial Economics, Case Western Reserve University, Cleveland, Ohio.

ROBOTICS, PROGRAMMABLE AUTOMATION AND INCREASING COMPETITIVENESS*

Bela Gold**

More than 25 years of empirical research on the productivity, cost and other effects of major technological innovations in a wide array of industries in the U.S. and abroad have led me to draw two conclusions:

First: that the actual economic effects of even major technological advances have almost invariably fallen far short of their expected effects; and

Second: that such exaggerated expectations have been due to their overconcentration on only a limited sector of the complex of interactions which determine actual results.

Hence, sound analysis of the prospective effects of increasing applications of robotics in domestic industries on their cost effectiveness and international competitiveness requires avoidance of such over-simplifications.

Accordingly, Part I of this paper will present some foundations for policy analysis, including: the place of robotics within current and prospective advances in manufacturing technology; the effects of increasing robot utilization on productivity and costs; and the resulting effects on international competitiveness. Part II will then consider the problems and policy implications of seeking: to accelerate the development of robotics and related advances in manufacturing technology; to accelerate the diffusion of such advances within domestic manufacturing industries; and to mitigate any potentially burdensome social and economic effects of such developments.

I POLICY ANALYSIS FOUNDATIONS

A. Robotics and Programmable Automation in Manufacturing

1. Programmable Automation

Gains in the physical efficiency of manufacturing operations may be derived from a variety of developments. The most important among these include: advances in technology; increases in the scale of production; improvements in the output and quality capabilities of equipment; adjustments in labor contributions; and continuing increments in the effectiveness of production planning and control. Because the effectiveness of such operations depends on integrating all these factors, changes in any one are likely to interact with others. Hence, evaluation of the effects of any innovation requires consideration of all resulting readjustments in the system.

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After basic advances in technology, the most important and continuous source of gains in the physical efficiency of production operations in the past has probably been increases in the specialization of facilities and equipment. The degree of specialization which was found most rewarding was determined by the variety and volume of output which needed to be processed by the given equipment. Thus, increases in the standardization of products and in the quantity required encouraged the introduction of progressively more narrowly specialized production systems. Eventually, the manufacture of completely uniform products in very large quantities led to the construction of interlocking arrays of highly specialized machines capable of producing enormous quantities with very great physical efficiency. Such "dedicated systems", however, permit only minor adjustments in product designs or processing methods. As a result, they are not applicable to the overwhelming proportion of manufacturing activities which involve the production of wider arrays of products in smaller quantities. In addition, the heavy investment required by such dedicated systems, combined with their very limited flexibility, also encourages their users to resist changes in products and improvements in production methods in an effort to use their existing equipment as long as possible.

Of course, engineering design permits a wide range in the extent to which specialization is built into production machinery. Thus, "general purpose" equipment may be designed to accommodate a wide array of tools and processing functions in return for limiting its rate of output as well as other capabilities in respect to any particular task. Such equipment's output is also heavily dependent on the concomitant specialized contributions of operators and other service personnel. And intermediate degrees of equipment specialization have offered progressively larger trade-offs of decreases in the range of functions capable of being performed, as well as decreases in reliance on the specialized contributions of operators and other external inputs, in return for increases in the level of output, quality and effectiveness of designated production tasks.

As a result of intensifying market pressures, there have been sharply increased efforts in recent years to improve the cost competitiveness of manufacturing operations devoted to a limited variety of products required in volumes ranging from relatively small to moderate. Such needs are dominant in most small and intermediate manufacturing plants as well as even in large plants manufacturing capital goods. By far the most important advance in such capabilities has come from the development of computerization and related communication and instrumentation capabilities. These permit the utilization of replaceable programmed instructions in combination with programmable controls to enable given equipment to turn out varying amounts of a succession of different parts with little or no operator requirements.

In order to help clarify the broad potentials of the resulting revolution in manufacturing technology which will be unfolding with accelerating rapidity over the next decade, it may be useful to illustrate the interconnected changes being generated as a result. Increasingly, the process will begin with computer-aided design (CAD), with engineers developing new designs on the screen of a terminal by specifying certain points on the screen and tapping instructions concerning the desired shapes and dimensions of the configurations to be drawn around them. The key point to understand is that in the course of projecting the design shown on the screen the computer is storing a detailed mathematical model of all of its features. It then becomes possible to use this information, or data base, for an expanding array of purposes. For example, the resulting definition of the dimensions and configurations of the designed part may be used in computer programs to generate such manufacturing requirements as:

1. a schedule of the sequence of machines to be used in producing the part;
2. specific operating instructions for each machine as well as identification of the tools required to perform such operations;
3. dimensional criteria for testing conformance of the finished part with design requirements;
4. production schedules specifying individual machine assignments to accord with estimated machining time required for each part and with previously scheduled machine loadings as well as delivery dates;
5. estimates of the unit cost of each operation, including the wages of the operator;
6. estimates of total unit costs of producing specified products may be used to determine bids for contracts; and

7. combining the design data with materials specifications and planned output, along with expected scrap rates and waste, to generate procurement requirements.

As indicated in Figure 1, various other kinds of performance evaluation and control information may also be generated.

By tracing only one direction of such information flows, however, even the preceding impressive array of applications understates the potential benefits of such systems. In fact, all such flows move in both directions. Engineers can use them to explore the relative costs of alternative designs. Manufacturing specialists can evaluate alternative processing sequences and machining instructions. Inventory adjustments can be adapted to accord with production and distribution variations. Production requirements and manpower availabilities can be adapted to one another.

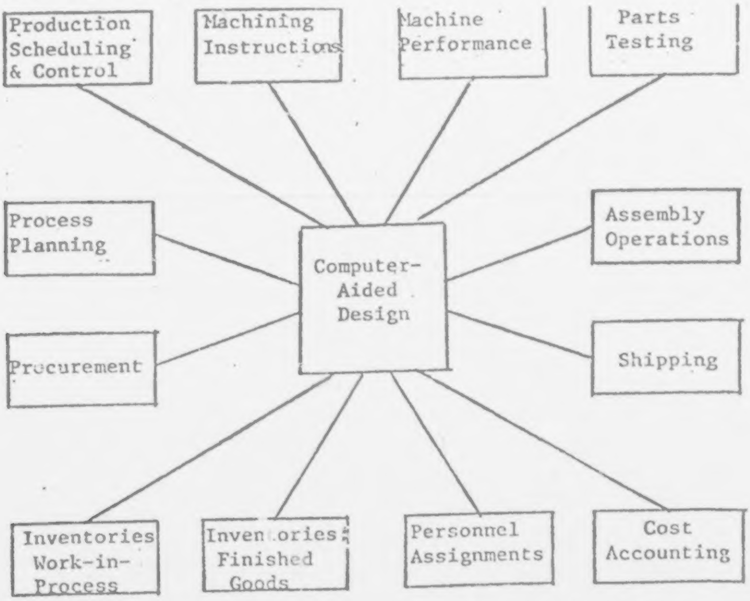
Production Scheduling & Control
Machining Instructions
Machine Performance
Parts Testing
Process Planning
Computer-Aided Design
Assembly Operations
Procurement
Shipping
Inventories Work-in-Process
Inventories Finished Goods
Personnel Assignments
Cost Accounting

Figure 1: Potential Applications of Design Data Bases

Programs have already been developed to apply each of the possibilities cited above. But few plants are actually utilizing many of them on a continuing rather than an experimental basis. Despite the clarity of the logic involved, the development of a functioning system requires confronting very large masses of details and many alternative possibilities at most stages of defining sequential decisions. There can be little doubt, however, that the future will see increasing realization of such potentials with profound effects on the requirements for remaining competitive.(1)

2. On the Role of Robotics Within Programmable Automation

Most robots are used in manufacturing as mechanical replacements for formerly manual operations. Major categories of such assignments include "pick and place", "manipulate" and "process". Essentially, the first involves transferring individual parts from one location to another, the second usually involves bringing parts together, as in assembly, and the third involves carrying out actual operations, such as welding or painting or testing. The complexity of these efforts may be enhanced if the robot is required to select among several objects through identifying key characteristics, or if it has to sense proximity to its target location, or if it has to adapt its manipulative or processing efforts to variable conditions. Efforts to extend the range of applications of robots have accordingly involved shifting increasingly from mechanically guided and controlled models to those which are programmable, equipped with feedback controls, capable of some degree of "learning" and possessed of a wider array and more sensitive manipulative potentials. Thus, in the perspective of labor-replacement objectives, developmental programs have sought to supplement the greater strength, speed, fatigue resistance and imperviousness to boredom of robots with increasing such capabilities as visual discrimination, precision of location and movement, and sensitivity to touch, pressure and torque.

Robots have commonly taken the form of separate pieces of equipment which are readily movable from one location to another. This obviously yields advantages of mobility comparable to the relocation of operators to adjust to changes in production needs. But the performance of what have come to be considered as "robot-like" functions need not be restricted to such separate mobile units. Indeed, the development of flexible manufacturing systems (FMS), or programmable automation systems, may well involve new combinations of "built-in" robot-like functions. In the case of machining centers, for example, instead of using a separate robot to select needed tools from a rack and then attach and remove them in proper sequence, this capability is built into the equipment. Various kinds of machines also have built-in capabilities for grasping, loading, unloading and passing parts along. And still others include devices for testing the conformance of finished parts with dimensional requiremnnts.

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(1) For further discussion, see B. Gold, An Improved Model for Managerial Evaluation and Utilization of Computer-Aided Manufacturing: A Report to the National Research Council Committee on Computer-Aided Manufacturing, Washington, D. C., March 1981.

The point being emphasized is that continuing development of programmable automation systems may well involve changes in the physical forms as well as in the functional capabilities of robot-like contributions to production. Physically separate units may be increasingly supplemented by replaceable attached units to service the changing requirements of particular machines, as well as by built-in robot-like capabilities in cases where the need for such services is expected to be continuous and to remain within a range which can be met effectively -- thus, many labor-replacing robots may themselves be replaced. Indeed, the very development of improved capabilities in robots may stimulate the redesign of later equipment to incorporate some of these additional functions. Hence, while it may remain feasible to assess the prospective effects of many individual robot applications, an increasing number of cases may require a broader evaluative context in order to ensure consideration of their interactions with other inputs as well as of other factors affecting performance in tightly integrated production operations.

B. ROBOTICS, MANUFACTURING PRODUCTIVITY AND COSTS

1. On the Concept and Measurement of Productivity

Despite widespread concern about lagging productivity in many U.S. industries, analyses of the problem and proposed improvement policies are still seriously handicapped in several ways. The most serious of these involves continuing reliance on inadequate concepts and misleading measures of productivity, such as "output per man-hour" or "value added per man-hour" or the supposedly sophisticated "total factor productivity" -- all of which can be shown to be of dubious value, when not actually misleading, for managerial purposes.

For example, "output per man-hour" has nothing to do with the effectiveness of production as a whole, or even with the effectiveness of labor contributions to output. By comparing the combined product of all inputs with the sheer volume of paid hours by one input, it patently ignores changes in the volume and contributions of all other inputs. "Value added per man-hour" repeats this error of attributing changes in output to only one of the inputs, but also encourages interpreting mere increases in wage rates, because they enter into value added, as evidences of increased "labor productivity". The grandly labelled "total factor productivity", on the other hand, is so overly aggregative as to make interpretations of resulting changes both difficult and highly vulnerable. Specifically, how is one to interpret changes in its ratio of "product value at fixed product prices" to "total costs at fixed factor prices"? Do they represent changes in deflated profit margins, or changes in the ratio of product price to factor price indexes, or changes in product-mix, or changes in a variety of other relevant factors including some aspects of productivity?

In addition to such erroneous concepts and measures, prevailing discussions of productivity problems and remedial policies are also undermined by highly vulnerable deductions about the causes of apparent changes in productivity levels and by dubious claims about the effects of productivity adjustments on costs and profitability. As a matter of fact, findings that output per man-hour, or value added per man-hour, or total factor productivity had increased or decreased by 5 per cent last year would reveal nothing to management about: what had caused this change; or how rewarding or burdensome it was; or what might be done to improve future performance.

In order to serve the practical requirements of management, a productivity measurement and analysis system must encompass all of the inputs whose interacting contributions determine the level of output and the effectiveness of production operations. For this purpose, one approach which has been applied in a wide array of industries utilizes the concept of a "network of productivity relationships". As shown in Figure 2, it encompasses the six components which management can manipulate in seeking to improve production efficiency: three representing the input requirements per unit of output of materials, labor and capital goods;(2) and three more representing the proportions in which these are combined with one another. The latter obviously need to be included because management could, for example, substitute more highly processed inputs in place of using some of its own labor or equipment, or it could substitute more equipment to replace labor. The inter-connectedness of these six elements emphasizes that a change may be initiated in any one, but that its effects must then be traced around the entire network to ensure that all adaptive adjustments have been made which are necessary to reintegrate the system. This also means that an observed change in one of the links need not have been engendered in that link, but rather have resulted as an adjustment to a change induced elsewhere in this system.

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(2) Fixed investment is related to capacity rather than to output, however, because that is what capital goods provide. Actual output may then vary with demand, entailing varying levels of idleness of such equipment. In measuring the proportions in which the major inputs are combined with one another, however, labor and materials inputs are compared not with total fixed investment but with actively-utilized fixed investment, i.e., with fixed investment adjusted for the ratio of output to capacity.

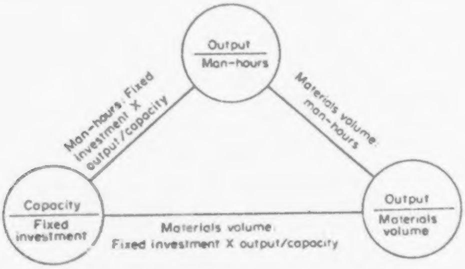
Output
Man-hours
Man-hours: Fixed investment X output/capacity
Materials volume: man-hours
Capacity
Fixed investment
Output
Materials volume
Materials volume: Fixed investment X output/capacity

Fig. 2 · The network of productivity relationships among direct input factors [9].

For example, mechanizing some manual operations would first affect the ratio of actively-utilized fixed investment to man-hours. This would tend to reduce man-hours per unit of output, while the attendant increase in fixed investment might alter its ratio to capacity. And if the innovation reduced scrap rates, it would also decrease the materials input volume per unit of output.

Because management's primary motivation in altering productivity relationships is usually to improve its cost competitiveness, it is necessary to evaluate past or prospective changes in the productivity network by tracing resulting effects on the cost structure. This involves, first, tracing the interaction of changes in each unit input requirement with its factor price to calculate resulting changes in its unit cost. For example, a 10 per cent increase in output per man-hour would yield only a 5 per cent reduction in unit wage cost, if it were accompanied by a 5 per cent increase in hourly wage rates. In turn, the effects of resulting changes in various unit costs on total unit costs depend, of course, on their respective proportions of total costs, as shown in Fig. 3.

Thus, the preceding example of a five per cent reduction in unit wage costs would tend to reduce total unit costs by only one per cent if wages accounted for only 20% of total unit costs. And total unit costs need not have declined at all if the assumed ten per cent increase in output per man-hour had been engendered by increased investment in machinery, or by purchasing more highly processed and hence more expensive material inputs.

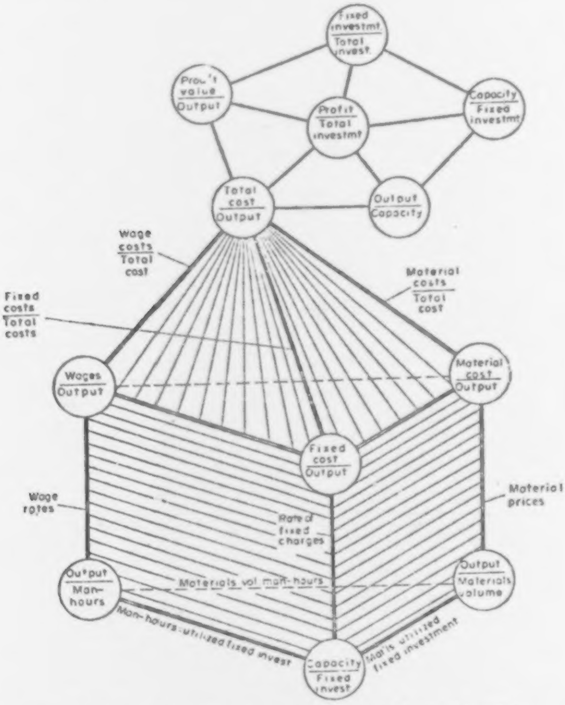
Fixed investmt / Total invest.
Prod't value / Output
Profit / Total investmt
Capacity / Fixed investmt
Total cost / Output
Output / Capacity
Wage costs / Total cost
Material costs / Total cost
Fixed costs / Total costs
Wages / Output
Material cost / Output
Fixed cost / Output
Wage rates
Material prices
Rate of fixed charges
Output / Man-hours
Materials vol man-hours
Output / Materials volume
Man-hours-utilized fixed invest
Capacity / Fixed invest
Mat'ls utilized fixed investment

FIG. 3 Productivity network, cost structure and managerial control ratios.

Management tends to be even more concerned about the effects of prospective innovations on profitability than on costs. Hence, account must be taken of the fact that such effects involve not only the direct impact of changes on total unit costs, but also the indirect effects of any changes in product quality or product-mix on product prices and capacity utilization rates. In addition, profitability would also be affected by any changes in the proportion of total investment allocated to fixed investment and in the productivity of fixed investment. But this discussion will not pursue such further ramifications. It may be of interest to add, however, that the above analytical framework can be disaggregated from plant level results to results within individual product lines or individual cost centers, and it can also be decomposed to trace the effects of changes among various components of material, labor or capital goods inputs.(3)

2. Exploring Productivity and Cost Effects of Robotics and Programmable Automation

The preceding framework may now be used to trace the prospective effects of increased applications of robots and of broader systems of programmable automation.

Within the network of productivity relationships, the immediate impacts of introducing additional robots would tend to center around increases in fixed investment and reductions in labor requirements per unit of output. In cases where the utilization of machine capacity had been restricted by the sustainable speed of labor efforts, output capabilities might be increased. And in some processing operations, robots might reduce the reject rate or even raise the average quality of output. Of course, part of the reduction in direct man-hour requirements would tend to be offset by the need for providing additional skilled maintenance and set-up personnel as well as programming capabilities when required.

These indirect manpower requirements emphasize the need to consider the prospective effects of individual robot applications separately from the effects of robotization programs, especially when more complex programmable robots are involved. Simple mechanical robots which are introduced as direct replacements for labor without altering other componenst of the production process offer no special evaluation problems. But the requirements of more complex programmable robots for various types of skilled servicing technicians and even engineers involves the assumption of substantial specialized and relatively fixed minimum manpower commitments. Hence, the effectiveness with which these are utilized depends on the number and variety of robots to be employed. Indeed, such manpower requirements might offset most or all of the expected benefits of reductions in operator man-hours if the number of robots acquired were too small to utilize such additional expertise. Because of such threshold requirements, the evaluation of proposals for the acquisition of more complex robots should cover the planned program to be carried out over several years rather than charging the whole of such basic service manpower requirements against the first robots acquired.

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(3) For more detailed discussion of this analytical approach and for some empirical findings resulting from its applications, see B. Gold, Productivity, Technology and Capital: Economic Analysis, Managerial Strategies and Government Policies (Lexington, MA: D.C. Heath - Lexington Press, 1979).

As was indicated earlier, the effects of increasing the use of robots on unit manpower costs depends on resulting changes in the volume of direct and indirect manpower per unit of output and in their respective rates of payment. In the case of relative simple robots which replace labor and involve quite minimal demands on existing maintenance and set-up personnel, the result tends to be a sharp reduction in the unit wage cost of the particular operation which was affected. In the case of adoptions of more complex robots, such reductions in direct unit wage costs would tend to be at least partly offset by increases in the number of needed maintenance and other specialists as well as by their higher average earnings. The net effects on total unit manpower costs would depend then on the output levels over which these larger indirect costs were distributed. Thus, because of the decreased flexibility in employment levels for such service personnel, attendant changes in output levels may have a significant effect on total unit manpower costs as well as on total unit capital charges. But the introduction of robots is not likely to affect output levels except, as was noted earlier, where operator limitations of effort, fatigue or carefulness have resulted either in under-utilization of the related equipment capacity, or in higher reject rates (thus involving higher unit material costs as well) — or where robots are subject to significant periods of unexpected downtime for repairs or readjustments.

Expected changes in the total unit costs of the operation directly affected can then be readily calculated by weighting the estimated percentage change in unit materials, labor and capital costs by their respective proportions of total costs, as shown in Fig. 3. In the case of more complex robots, however, as exemplified by processing and assembly robots, a broader evaluation framework may be necessary if the effective functioning of such robots requires modifications in prior operations in order to provide more precise or higher quality parts to enter such processes. A broader evaluation framework may also be necessary if such robotized operations significantly affect the productivity and costs of subsequent stages of operations, or the quality of the final product in ways affecting prospective demand or prices.

In short, the increasing diffusion of robots is likely to make only a modest, though still significant, contribution to improving the cost effectiveness of most manufacturing firms. One of the basic factors limiting such potential benefits is that direct wage costs seldom account for more than 15-25 per cent of total costs and any savings through reducing direct man-hour requirements tend to be partly offset by increases in capital charges and in indirect wage and salary costs, and further offsets would be generated if wage rates are increased to help gain acceptance of such innovations. An additional limitation on such potential benefits arises from the fact that only a narrow array of tasks can be performed more economically by robots than by labor or by machines which include the robotizable capabilities. Indeed, even some of the manual functions which can be economically transferred to robots now may in time be transferred into redesigned machines, as was noted earlier.

From the standpoint of longer term planning perspectives, consideration should also be given to a plant's cost proportions and to the prospective effects of increasing the ratio of "fixed" to "variable" costs. Cost proportions differ very widely, of course, among industries as well as among plants within industries. The long term average proportion of total costs accounted for by actual wages in U.S. manufacturing has been well under 20 per cent, ranging between less than 10 per cent in ore smelting, petroleum refining and other industries which represent the first stage of processing natural resources to more than 40 per cent in industries involving the fabrication of complex machinery.(4) Thus, the prospective effects of robotization on total unit costs through reductions in unit wage costs would tend to be far greater at the latter extreme. Attention must be given not only to the magnitude of cost proportions, however, but also to the extent to which a given category of unit costs could be reduced through robots or other innovations. Thus, any resulting increases in output per man-hour which are largely or wholly offset by attendant increases in hourly wage rates would yield little or no cost advantage, however large the wage cost ratio -- especially if account is also taken of the associated increase in capital charges. On the other hand, sight must not be lost in such evaluations of the powerful leverage of reductions in total unit costs on profit margins, for even a 5 per cent reduction in total unit costs could increase profit margins by 33-50 per cent. Hence, the relative magnitudes of wage cost proportions warrants careful consideration in choosing targets among different sectors of operation for robotics applications whose benefits are expected to center on wage savings.

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(4) For a comparison of cost proportions in 20 manufacturing industries, see B. Gold, Explorations in Managerial Economics: Productivity, Costs, Technology and Growth (London: Macmillan, 1971; New York: Basic Books, 1971), p. 137. Japanese translation - Tokyo: Chikura Shobo, 1977. Differences in cost proportions among plants in the same industry are attributable primarily to differences in their "make vs. buy" ratios, in the modernity of their technologies and facilities, in their scale of operations and in their product-mix. For further discussion, see B. Gold, "Changing Perspectives on Size, Scale and Returns: An Interpretive Survey", Journal of Economic Literature March 1981, especially pp. 21 et.seq.

Longer term planning for advancing manufacturing technology has also been affected in many industries by the traditional concern about the burdens of increasing the ratio of total capital charges, which are considered "fixed", to labor costs which are considered "variable"-- meaning that the former are unaffected by reductions in output, while the latter decline with them. But it is obvious that labor costs have become less "variable" because of trade union resistances to reductions in employment and wage rates, and because of increasing cost penalties for lay-offs through "social benefit" requirements. Increasing attention has also been given in recent years to adjusting depreciation rates in response to changing levels of capacity utilization, thus enhancing the variability of total capital charges.

The possibility should also be considered that capital inputs are becoming progressively more economical than labor inputs as compared with their respective contributions to output. In part, this reflects the fact that continuing technological progress tends to enhance the production contributions of facilities and equipment far more than those of labor. Moreover, although capital goods prices and wage rates both rise during inflationary periods, the prices to be paid for the former stop rising as soon as they are purchased, while wage rates continue to rise even after workmen are hired,and might rise even more if "higher labor productivity" can be claimed as a result of the additional equipment. Indeed, the costs of using such capital goods may even decline steadily under some forms of depreciation. In addition, most increases in capital facilities involve some, and often substantial, replacements of labor inputs, thus helping to offset part of the capital costs. Still another factor tending to increase the relative economy of capital inputs is the seemingly irreversible trend towards increasing payments to labor for non-working time, including:lay-offs; sickness; holidays; vacations; and pensions. Altogether, these considerations suggest that, in addition to altering past characterizations of capital and labor costs as "fixed" or "variable" in response to output fluctuations, attention should be given to characterizing the long term tendencies of capital and labor costs -- with indications that the latter may warrant classification as "rising" relative to the former.

Evaluating the prospective effects of advances in computer-aided manufacturing, or programmable automation also requires more complex considerations as well as still broader coverage and even longer time perspectives. Briefly summarized, they are likely to affect all unit input requirements as well as the factor proportions encompassed by the "network of productivity relationships", they tend to alter longer term trends in capacity levels as well as in capacity utilization, and their effects are likely to reach beyond production operations to modify managerial planning and control systems as well as the organizational structure of firms.(5)

C. ROBOTICS, MANUFACTURING TECHNOLOGY AND INTERNATIONAL COMPETITIVENESS

1. Some Basic Perspectives on the Determinants of International Competitiveness

The growing national concern with the declining international competitiveness of a significant array of major U.S. industries has generated a stream of proposals for remedial action. Unfortunately, most of these are based on untested assumptions about the general causes of such lagging competitiveness instead of on penetrating analyses of the specific industries affected.

It is important to recognize that foreign competitive pressures no longer concentrate only on older industries with mature technologies. On the contrary, such pressures are intensifying over a wide spectrum of "high technology" industries as well. Examples of the latter include: semi-conductors, computers, telecommunications, sophisticated robotics, aircraft and flexible manufacturing systems. Hence, following the panic-induced proposals to abandon our older industries, which are also major sources of employment and income, would merely intensify problems of domestic welfare and military security. It is important, of course, to foster the development of newly emerging industries because, although they are likely to make only modest contributions to employment, income and foreign trade during their first 5-10 years of development, some of them may become powerful sectors of our economy in the future. But encouragement and support for such embryonic industries must be supplemented by intensified efforts to re-establish the competitiveness of older major industries through advancing beyond their current technological frontiers, if the national welfare is to be safeguarded in the short-run and intermediate-run as well.(6)

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(5) For a brief summary of some of these effects, see B. Gold, "Revising Managerial Evaluations of Computer-Aided Manufacturing Systems", Proceedings of the Autofact West Conference, Vol 1 (Deaborn, MI: Society of Manufacturing Engineers, Nov. 1980). For a more detailed report, see B. Gold, An Improved Model for Managerial Evaluation and Utilization of Computer-Aided Manufacturing: A Report to the National Research Council Committee on Computer-Aided Manufacturing Washington, D. C., March 1981.

A related view whose vulnerability is inadequately recognized holds that the international competitiveness of our basic manufacturing industries is bound to decline relative to less developed countries because of our higher wage rates. Of course, substantial wage rate differentials do exist and these are likely to encourage continuing shifts in the location of some light manufacturing industries. But such wage rate disadvantages are largely offset in many basic industries by higher output per man-hour and higher product quality. In addition, the tendency for wage rates to rise more rapidly in industrializing countries tends to further reduce resulting differences in unit wage costs. It is also worth recalling here that wages tend to account for less than 20 per cent in U.S. manufacturing as a whole, thus limiting the effects of lower wage rates in wide sectors of industry. Most important of all for the longer run is the fact that labor inputs are being replaced increasingly in determining the productive efficiency of most manufacturing industries by capital inputs, which embody the technological contributions of advances in processing, mechanization, computerization, programmable controls and robotics. Hence, advanced industrial nations are likely to retain their competitive advantages in many basic manufacturing industries for many years to come. Such advantages will be reinforced by the greater availability of investment funds and the greater availability of the advanced engineers and highly skilled labor needed to maintain, supervise and improve such sophisticated operations -- especially those producing higher quality and more complex products.

At any rate, more sharply focussed diagnoses are obviously essential to the development of effective remedial efforts, not only for the industries which have already been hard hit by foreign competitors, but also to help the additional array of domestic industries likely to face such increasing pressures during the next five years. In this connection, it may be worth noting some of the findings emerging from a study of the factors affecting the international competitiveness of a sample of domestic industry being conducted with the support of the National Science Foundation.(7) Contrary to widespread assumptions and beliefs, the major causes of the decreasing international competitiveness of various domestic industries differ widely among industries. Hence, generalized solutions are likely to result in only mild palliatives at best. Also, although decreasing competitiveness in production efficiency is a major factor in a number of industries; such shortcomings are powerfully reinforced, and sometimes even over-shadowed by:

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(6) For further discussion, see B. Gold, "U.S. Technological Policy Needs: Some Basic Misconceptions," in H.H. Miller (ed.), Technology, International Economics and Public Policy (Washington, D. C.: American Association for the Advancement of Science, 1981).

a. Product designs which are less efficient, less attractive, less trouble-free or less sensitive to changes in consumer preferences;
b. Higher unit wage costs resulting from wage rate increases which have outrun gains in output per man-hour;
c. Higher unit costs of raw materials, energy, capital goods, or investment funds; and
d. Less aggressive marketing and less responsiveness to customer delivery and servicing needs.

Third, even disadvantages in respective to production efficiency are due to a variety of causes. Less advanced technological processes, older facilities and more limited utilization of computer-aided manufacturing and robotics have certainly been important handicaps. But it would be a mistake to under-estimate the influence on strengthening the competitiveness of various foreign producers of such factors as: more aggressive managerial demands for productivity improvement; larger technical staffs under greater pressure and more effectively motivated to increase technological capabilities; and reliance on longer production runs of a more limited product-mix to help keep capacity utilization rates high.

Fourth, another important contributor to the production efficiency of some foreign producers has been their labor's greater productive efforts, greater willingness to accept and maximize utilization of technological advances and improvements, and greater mobility among tasks. But blaming a large share of the decreasing competitiveness of domestic industries on general declines in the capabilities and motivations of labor tends to be contradicted to some extent by the high quality of output and the apparent cost effectiveness of some foreign-owned plants in the United States. This does not mean that all trade unions have supported the introduction of technological advances, have co-operated in efforts to raise productivity levels to those achieved by foreign competitors, and have limited demands for increases in wage rates to match increases in their contributions to production capabilities. But it does mean that some foreign managements -- and some domestic managements as well -- have found it possible to work with domestic labor in ways which yield high quality products, high productivity and competitive costs. Here again, therefore, the need is to dig beneath superficial generalizations to come more closely to grips with the factors which are most influential in various sectors of industry, and under different conditions.

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(7) The author is Chief Investigator. The report is scheduled for late 1981.

2. Potential Contributions of Robotics and Programmable Automation to Improving International Competitiveness

The potential contributions of robotics and programmable automation to improving the competitiveness of domestic manufacturing industries must be examined within the context of the preceding complex of influential factors.

Increasing the utilization of progressively improved robots would obviously tend to have a positive effect on technological competitiveness. But the resulting gain is likely to be of only modest proportions in most plants and industries unless such advances are integrated with simultaneous advances in other determinants of technological competitiveness. Roboticizing manual operations in old plants using old machinery to make old products has obviously limited potentials. Nor are major advances likely to result from improving any other single component of the interwoven fabric of changes underlying significant progress in technological competitiveness. Robotics can undoubtedly make substantial contributions to such progress, but only as part of a comprehensive program to improve technological competitiveness.

Such programs must encompass carefully co-ordinated plans seeking to improve the capabilities and attractiveness of products, to adopt advanced technologies, to embody them in modern equipment of a scale deemed close to optimal for the level of output and product-mix to be provided, to provide for progressively adjusting input factor proportions and equipment utilization practices so as to maximize production efficiency, and to ensure continuing efforts to improve performance. It would be impractical, of course, to attempt to advance on all of these fronts simultaneously. But it would also be frustrating and wasteful to attempt to make major advances along any of these channels without considering prospective interactions with, and possibly offsetting pressures from, these other components.

Moreover, recognition of the complexity of the elements involved in achieving significant advances in technological competitiveness must be combined with appropriate time perspectives both in setting improvement targets and in planning progress towards them. In setting targets, it is important to base them not on catching up with the current capabilities of competitors, but on careful evaluations of prospective improvements in their capabilities over the next 5 years, along with parallel evaluations of prospective changes in the availability and prices of all required inputs, as well as in the output levels, mix and prices of products likely to be experienced in the market place. And in planning progress, realistic assessments need to be made of the likely availability of capital, of the time needed to acquire needed facilities and equipment and for management, engineers and labor to learn to use them effectively, as well as of the constraints likely to affect the rate of adjustments in employment levels and organizational rearrangements.

II SOME BASIC POLICY ISSUES AND ALTERNATIVES

A. BASIC ISSUES

Although it has already been emphasized that the declining international competitiveness of an increasing array of domestic manufacturing industries is attributable to a variety of factors, there can be no doubt that lagging technological competitiveness and related production efficiency is one of the leading causes. Such lags are due to belated and inadequate adoption of successful technological advances available from abroad, to inadequate modernization of facilities and equipment, to inadequate improvements in production management and controls, and to continued shortcomings in gaining labor co-operation for maximizing the cost and quality competitiveness of products.

Within this array, programmable automation is especially important not only because it can contribute to each of the others, but, above all, because it represents an essentially general process of progressive advances in technological capabilities and productive efficiency. Instead of offering the particular localized benefits of any single improvement in process technology, or in the capability of a new machine, programmable automation may be regarded as a form of "contagious" technology which keeps pressing to surmount the boundaries of any given application and thereby to "infect" adjacent sectors of operations and controls. It may, of course, be applied beneficially to single operations, but its major potentials derive from providing the means of achieving increasingly optimal functioning of each production unit, increasingly effective integration of all components of production, and increasingly effective co-ordination and control of other non-production operations as well -- as was illustrated in Figure 1.

Robots have been and will, of course, continue to be introduced simply as direct replacements for individual workers performing manual tasks. But an increasing proportion of their applications in the future are likely to derive from the continuing development and spreading of programmable automation systems, which are likely to require comparably improving capabilities in their robot components.

Accordingly, the key issues involved in increasing the contribution of programmable automation and robotics to strengthening the international competitiveness of domestic manufacturing industries would seem to center around:

1. the adequacy of the rate of development of the technological capabilities of programmable automation systems and of robotics relative to the rate of progress abroad;
2. the adequacy of the rate of diffusion of programmable automation systems and of robotics relative to their capacity to improve productive efficiency and cost competitiveness, and also relative to such diffusion rates among foreign competitors;
3. the relative effects of slower and faster rates of development and diffusion of such systems and of robotics on the competitiveness of various domestic industries as well as on their employment levels and capital requirements; and
4. the identification of the nature, sources and relative importance of the influential determinants of changes in the rate of development and diffusion of programmable automation systems and robotics.

The formulation of effective approaches to encouraging fuller realization of the constructive potentials offered by programmable automation systems and robotics would seem to require prior careful exploration of these issues.

B. SOME POLICY NEEDS AND ALTERNATIVES

1. On the Adequacy of Development Rates

Until now, most of the development efforts concerned with programmable automation and robots have been focussed on performing existing tasks more effectively or more safely. Because of the already recognized needs of managements and the consequent easing of marketing problems, early robot applications were designed to replace workers in dangerous or uncomfortable working environments, then in tasks involving heavy physical demands, and only later and more gradually in highly repetitive tasks. Most such past applications required few advances in technology, primarily representing new forms of specialized machine designs.(8)

Although later applications have required somewhat more complex operating and control capabilities, developmental efforts have continued to be dominated by the objective of performing existing jobs faster or more accurately. And this approach is likely to continue among robot manufacturers because of the inevitably narrow set of functions to be performed by any one of their products and the consequent need to satisfy the completely pre-defined parameters of the component tasks to be performed. Research frontiers would accordingly concern improving manipulative capabilities, increasing the precision of actions taken, enhancing the reliability and durability of operations, and broadening the functions of programmable controls through extending the range of human senses which can be duplicated and through improving provisions for adaptive adjustments and "learning".

It is difficult to find persuasive data concerning relative progress in the development of robot capabilities in different countries. Active efforts have patently been under way for some years in Western Europe, Japan and the United States as well as in Eastern Europe. And impressive products have been marketed by producers from each of these areas. American manufacurers have been especially complimentary about the reliability of Japanese robots and about certain capabilities of Swedish and Italian robots, while also praising a number of domestic products. But the readiness of current and prospective American users of robots to rattle off a long list of specific limitations which tend to narrow the range of immediately rewarding applications much more sharply than is suggested by general discussions indicates that increased research and development may open the way to a major expansion of practical robot applications in domestic industries. And resulting innovative advances might well engender the rapid growth of the domestic robot manufacturing industry in addition to accelerating increases in the productive efficiency of robot-using domestic industries.

This raises the question of whether any additional measures should be considered by the government to augment the limited but increasing efforts by private industry and universities to improve the capabilities and cost effectiveness of domestically produced robots. Some foreign governments have supported such efforts through research and development grants to industry and to universities and also through encouraging prospective users, especially in defense industries. Similar efforts have been made in this country, although probably on a more limited scale.

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(8) For an excellent review of robotics applications by a pioneer in their development, see J.F. Engelberger, Robotics in Practice (New York: AMACOM, 1980).

Turning to programmable automation, somewhat similar early developmental patterns may be noted. Initial applications tended to concentrate on developing process controls for individual production units. But the fact that computer manufacturers had a broader range of application potentials in view than robot producers resulted in a rapidly expanding concern with co-ordinating progressively wider sets of individual process controls and then integrating these into increasingly encompassing performance-monitoring and control systems. Although international surveys have called attention to some foreign systems which seem to be much more advanced than any in the United States, most of these seem still to represent uncommon cases of pioneering or largely experimental applications.(9)

Developmental efforts are under way in a number of domestic firms, especially those involved in aerospace programs, to extend applications of programmable controls to a variety of production, planning and control functions. But most of these have not yet reached the stage of reliable broad commercial applicability and none at all have achieved effective integration over a wide array of such functions. Moreover, both developmental efforts and applications have been of distinctly meager proportions in firms basically devoted to non-defense production. Hence the question arises in this connection, as it did in respect to robotics, whether any additional measures should be considered to augment the increasing, but still limited, efforts of private industry and of universities to accelerate the development of increasingly comprehensive programmable automation system.

Finally, increasing attention might well be given to the possibility that the development of programmable automation systems may engender an alternative approach to the development of robotic functions and forms. Specifically, in place of the past approach of roboticizing existing manual tasks, the designing of programmable

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(9) For example, see Dennis Wisnosky, Worldwide Computer-Aided Manufacturing Survey (Dayton, OH: Air Force Systems Command, December 1977) and also J. Hatvany, K. Rathmill and H. Yoshikawa, Computer-Aided Manufacturing: An International Comparison (Washington, D.C.: National Research Council Committee on Computer-Aided Manufacturing, Sept. 1981.)

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automation system may result in generating altered definitions of the kinds of functions to be considered for robotization, and may even integrate some of these functions into other machine or equipment components of the system. It may be relevant to mantion in this connection that progress in programmable automation is often discussed within the context of efforts to develop "automatic factories".(10) Although such achievements still seem far off in respect to plants capable of producing limited quantities of a variety of products economically -- as differentiated from continuous process petroleum refineries and chemical plants -- they exemplify the reverse orientation which is likely to become increasingly important: designing the plant as a whole and then defining the functions and needed characteristics of the component parts, instead of developing robots and programmable controls for a succession of individual operations within existing plant characteristics.

What are the policy implications of such observations? There is ample basis within the basic values of the American economic system for questioning the advisability of governmental support for efforts by private firms to develop appropriable commercial improvements in robot capabilities or in other technologies. But there are very cogent reasons indeed for recognizing the government's responsibility for supporting research and development programs seeking to extend and enrich the pre-commercial scientific and engineering foundations of increasingly effective industrial operations.

Most private firms seldom undertake technological development programs which are unlikely to reach commercial fruition in less than 5 to 8 years, including the time necessary to construct needed production facilities and to begin marketing their products. One of the most promising means of multiplying such private efforts would be to increase the array of technologies which have emerged from the often lengthy, costly and risky processes of intermediate development between basic research findings and a level of refinement deemed to be within striking distance of appropriable forms of commercialization. Moreover, such advances represent additions to national resources of knowledge which are likely to stimulate application efforts in many other sectors of the economy and social services, including office operations, construction, household services and health and rehabilitation activities.(11)

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(10) As an illustration of current efforts in this direction, see Proceedings of the Autofact West Conference (Dearborn, MI: Society of Manufacturing Engineers, Nov. 1980) Volumes I and II.

(11) For further discussion, see B. Gold, Productivity, Technology and Capital: Economic Analysis, Managerial Strategies and Government Policies (Lexington, MA: D. C. Heath - Lexington Books, 1979) pp. 302-303.

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It should also be noted that one of the most important future sources of technological competitiveness in manufacturing industries -- the development of increasingly encompassing systems of programmable automation -- has not yet advanced sufficiently to minimize the possibility that intensified domestic efforts might not only match but might even surpass foreign progress. It should be recognized, however, that vendors of particular components are not likely to make substantial investments in developing broadly comprehensive systems of programmable controls. Indeed, they are more likely to resist any such developments which might generate requirements for components with characteristics different from their own offerings. Moreover, few manufacturers are likely to develop programmable automation systems which are applicable beyond their own unique operating and organizational arrangements. Hence, the practical questions would seem to be: what span of operating and functional coverage would be applicable widely enough to warrant the investment in developing it? and who might consider it worth making such a commitment? Efforts to develop such systems in aircraft manufacturing plants are being supported by government agencies. And some private firms have joined in developing some common components of such systems. But no comprehensive review of what needs to be done, or what the benefits of more effectively organized efforts might be, is available at this time. Here, then, is another area in which governmental support may yield valuable contributions to advancing the competitiveness of domestic manufacturing.

2. On the Adequacy of Diffusion Rates

The impact of technological advances on market competitiveness is determined not by the location or rate of their development, but by the rate of their diffusion and the extent of their utilization. Although some observers claim that Japanese industry has surpassed the United States in the utilization of programmable automation systems as well as of robots, such applications still account for only very limited sectors of their manufacturing industries and are even sparser in Western Europe. Accordingly, there is still a wide open opportunity for domestic manufacturing to overcome its current lags in this area and thereby achieve major improvements in its productive efficiency and cost competitiveness.

What factors have retarded the more rapid diffusion of these technologies? Perhaps the most important influence has been the basic unawareness of most industrial managements of the far-reaching potentials of this burgeoning revolution in manufacturing technology. Such inadequate appreciation of these potentials may be attributed in part to the limited knowledge of such capabilities of most of the senior engineering officials responsible for advising top management about important technological developments. Another influential factor has been the tendency of firms to continue relying on processes for developing innovational proposals, and on capital budgeting models for evaluating them, which worked reasonably well for incremental improvements in established technologies in the past, but which have serious shortcomings in generating and evaluating proposals for major advances in technology like programmable automation.(12)

Such restricted perspectives have also been supported by the concentration of most vendors of programmable control systems and of robots on selling bits and pieces to the lower level officials concerned with the sub-sectors likely to be directly affected by their application, thus reinforcing the traditional view that technical innovations can best be evaluated by specialists in the operations immediately involved,instead of emphasizing the broader potentials rooted in these emerging technologies. Widespread awareness of the shortcomings and resulting penalties of some early applications have also encouraged disinterest in these developments. It is important to recognize in addition that most universities have been quite backward in recognizing the new potentials of manufacturing technology and of providing the educational programs and research facilities needed to train urgently needed specialists and to provide urgently needed advances in related knowledge.

There would be no basis, of course, for efforts by government to urge all manufacturers to adopt these innovations, inasmuch as differences in their needs and resources ensure that no advances in technology are equally attractive for all firms even in the industries most directly affected. But it might well be desirable for government agencies to undertake active programs to help develop fuller understanding in industry of the potentials and accomplishments, as well as the current limitations, of programmable automation systems and robotics -- including periodic reports on progress in the development and utilization of such advances abroad. And such agencies might well consider exploring with a reasonable array of universities the possibilities and desirability of expanding educational as well as research programs in various sectors of manufacturing technology -- and helping to finance the acquisition of needed facilities as well as some scholarship aid.

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(12) For a detailed discussion of these processes and models, see B.Gold, An Improved Model for Managerial Evaluation and Utilization of Computer-Aided Manufacturing: A Report to the National Research Council Committee on Computer-Aided Manufacturing (Washington, D. C., March 1981).

3. Effects of Altering Development and Diffusion Rates

Appraising the adequacy of current rates of adopting and utilizing programmable automation and robotics obviously requires consideration of attendant enbefits and burdens. Past adoptions of both have been sufficiently limited and gradual to engender little observable effects on the employment and skill requirements of the work force, while increasing the need for servicing personnel. This experience has engendered some unconvincing assurances that the accelerated diffusion of such technologies will not entail significant displacements of labor at the same time that others have emphasized the urgency of utilizing these advances in order to overcome serious shortcomings in cost competitiveness through the attendant reductions made possible in labor requirements.

The basic fact is that unemployment in any firm is caused primarily by a decline in its competitiveness. If it fails to adopt the technological advances utilized by competitors, its employment will decline much more rapidly than if it adopts such advances, even if these involve some displacement of labor. Moreover, for many domestic industries such effects represent costs which have already been exacted and which threaten to become even greater if technological lags are not reduced. Regaining competitiveness in some domestic industries may now require reductions in man-hour requirements per unit of output of at least 20-30 per cent.(13) Moreover, such lags are continuing to grow as foreign competitors' efforts to surpass American performance keep intensifying -- as may be illustrated by Japanese developments in the steel, automobile, machine tool and semiconductor industries. In short, major improvements in the performance of domestic industries is imperative. Hence, rejecting attempts to accelerate the diffusion of programmable automation and robotics could only be justified by identifying and then promoting other means of achieving the needed large advances in the productive efficiency and cost competitiveness of major industries within the next five years.

It should also be recognized that implementing the major advances in technology involved in accelerating tha application of programmable automation represents a much more difficult and far-reaching challenge to management than is generally recognized. The key reason for this is the failure to recognize that basic technologies are built not only into the production machinery, but also into:

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(13) For a comparison of labor requirements in the Japanese and U.S. steel industries, see B. Gold, "Steel Technologies and Costs in the U.S. and Japan", Iron and Steel Engineer, April 1978. Japanese translation in Jōhō Shūhō (Tokyo) July 1978.

a. the expertise of the technical personnel;
b. the structure and operation of the production system;
c. the economically feasible range of changes in product designs and product-mix;
d. and the very criteria used to evaluate the capabilities of new capital goods; as well as
e. the skills and organization of labor.

Each of these represents powerful and mutually reinforcing commitments to preserving existing operating and organizational arrangements, except for small, gradual and localized changes. Hence major advances are not likely to be achieved unless they are pushed aggressively by senior managers committed to achieve them and willing to invest the resources and to introduce the organizational means necessary to implement such programs.

4. Other Incentives and Deterrents

One of the most important stimuli to the increasing diffusion of robots has been the gradually growing awareness among managements, engineers and labor that these have proven themselves practical and economical in an expanding array of applications, and hence are becoming an increasingly unavoidable option among the alternatives to be considered whenever plans to improve productive efficiency are being developed. This fact alone has forced production managers and engineers to seek more information about robot capabilities, limitations and costs, thereby sensitizing them to the kinds of applications where they might prove most rewarding. And such inquiries from prospective customers obviously help to focus the development efforts of robot manufacturers on meeting newly emerging market opportunities.

On the other hand, one of the influential deterrents to more rapid adoptions of robots has been managerial concern about labor reactions. The introduction of robots to replace operators in dangerous or especially uncomfortable environments was readily accepted, of course, as was their use in unduly exhausting jobs. The use of robots in highly routinized ("boring") jobs has also been commonly accepted by labor provided that the replaced operators were given other assignments. But there seems to be widespread concern among managers that robot installations which threaten substantial employment reductions in existing plants may well engender serious labor problems, whose resolution would be likely to reduce expected cost-savings substantially. Major installations are accordingly likely to be restricted to new plants which can establish new manning levels in accordance with their new operating characteristics. Such managerial concerns need not, of course, prevent the increasing use of robots in older plants, but they would seem to encourage introducing robots only slowly and in scattered operations, thereby minimizing the rate of gains in productivity and cost savings while easing labor resistance. Only when an immediate threat to the survival of the plant is recognized by labor are such resistances likely not to inhibit major readjustments.

But it should be noted once again that large scale introductions of robots would seldom offer substantial economies anyhow, except as a means of implementing plans for broader programmable automation. And these can seldom be retrofitted into old plants, except through major modernization programs involving changes in production facilities and equipment as well as operating practices.

Consideration of large scale programs of programmable automation and roboticization, however, raises fundamental questions concerning the past balancing of prospective incentives and deterrents by managements, and the possible need to shift that balance to provide greater encouragement to undertaking the costly and risky commitments involved in developing and adopting major technological advances. Key elements would seem to include:

a. increasing the prospective profitability of longer term investments in advanced production facilities and in seeking to develop major technological improvements in processes as well as products;

b. increasing the availability of trained technical manpower to guide and manage such developments as well as the availability of a richer foundation of scientific and technological research and pre-commercial development as the basis for private commercialization efforts;

c. increasing labor recognition of the urgency of achieving major advances in cost competitiveness in order to ease threats to employment and also easing resulting burdens on labor resulting from co-operation in the utilization of technological innovations offering such advances.

Meeting such needs would seem to require substantial contributions from the government, from labor organizations and from universities as well as from industrial managements. And failure to meet such needs would probably exact penalties from each of these beneficiaries of an effective industrial economy.(14)

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(14) For more detailed discussion, see B. Gold, Productivity, Technology and Capital: Economic Analysis, Managerial Strategies and Government Policies (Lexington, MA: D. C. Heath - Lexington Books, 1979) Chapter 17. Also see B. Gold, An Improved Model for Managerial Evaluation and Utilization of Computer-Aided Manufacturing: A Report to the National Research Council Committee on Computer-Aided Manufacturing (Washington, D. C., March 1981).

PAINE WEBBER MITCHELL HUTCHINS

ROBOTICS AND ITS RELATIONSHIP TO THE AUTOMATED FACTORY

Eli S. Lustgarten

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This report was prepared for the Robotics Workshop of the Congressional Office of Technology Assessment held in Washington, D.C. on July 31, 1981.

Basic
Analysis

ROBOTICS AND ITS RELATIONSHIP TO THE AUTOMATED FACTORY

Paine Webber
Mitchell Hutchins Inc.

INTRODUCTION

More attractive technology, the end of the baby boom, the need to modernize an aging U.S. manufacturing base and to reduce the use of labor more expensive than most of our international competition, and a more favorable tax structure will lead to increasingly automated factories. One product, the robot, is likely to become a key building block in the penetration of factory automation into the manufacturing world. The purpose of this report is to provide a framework for analyzing the robot industry and its interrelationship with U.S. manufacturing techniques.

This report is divided into several sections:

- An overivew of the general status of U.S. manufacturing and the potential need for robots.
- An analysis of current and potential uses of robots.
- An analysis, from the robot producers' point of view, of the likely evolution of the robot market and key competitive factors.
- A discussion of the impact of robots on manufacturing operations.
- A discussion from both the producers' and users' point of view of capital availability and potential financial incentive programs which could foster the development of the robot industry.

OVERVIEW: REDISCOVERING THE FACTORY

The automated factory has been a dream of the manufacturing world. The production manager, always pressured to improve output, has been influenced by classical economists who ranked technological advancement as the most important determinant of productivity (38%), capital investment second (25%), with labor accounting for only 14% of the changes. However, U.S. business has had to operate in an exceptionally difficult economic environment during most of the 1970s, a period of rapidly increaisng inflation, exploding energy prices and gyrating money markets. These factors contributed to a decade of sluggish economic growth, weak research and development spending and economic policies that favored consumption over investment, resulting in real capital spending that significantly trailed the strong outlays of the 1960s. The 1.5% productivity growth during 1973-79 was half our historic average, with some economists suggesting that labor may have been the only factor in the classical equation that contributed more to productivity growth since 1973 than it did from 1948.

July 31, 1981

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	Real GNP Growth	Real Gross Private Fixed Investment	Real Producers Durable Equipment	Real P&E Spending	Productivity Growth
1959-72	3.8%	4.9%	5.7%	3.8%	3.1%
1973-79	2.5%	2.1%	2.8%	2.1%	1.5%

The economic environment of the 1970s also favored capital outlays that resulted in a quick payback. As economists Burton G. Malkiel has pointed out:

> "From 1948 to 1973 the (net book value of capital equipment) per unit of labor grew at an annual rate of almost 3 percent. Since 1973, however, lower rates of private investment have led to a decline in that growth rate to 1.75 percent. Moreover, the recent composition of investment (in 1978) has been skewed toward equipment and relatively short-term projects and away from structures and relatively long-lived investments. Thus our industrial plant has tended to age..."

The deline of the U.S. manufacturing base can clearly be seen by looking at the age of U.S. machine tools in place (Table 1):

- Two-thirds of all U.S. machine tools are over ten years old and one-third are more than twenty years old.
- The technological penalty is even more severe as sophisticated numerical control equipment has made only slight inroads into the manufacturing process.

By contrast, capital investment as a percentage of GNP in France and West Germany was more than 20% greater than that in the U.S., while in Japan the percentage was almost double ours.

Corporate managers, shocked by faltering productivity and loss of markets to international competition, have begun to perceive a connection between their deteriorating competitive positions and the neglect of the part of their businesses that actually produces goods. However, until recently, productivity was an economist's term rarely used by businessmen. It is now dawning on some managements that responsibility for their competitive listlessness cannot be blamed simply on the decline of work effort, unreasonable government regulation or a shortfall in capital investment. Rather, they are beginning to see it as symptomatic of something wrong with the way manufacturing operations are set up and organized.

As previously indicated, technological advancement, including improved management techniques and integration of the manufacturing process, is the most important factor in the classical equation for productivity. Hence, two related technologies, computers and robots, offer prime opportunities for improvement. U.S. industry today is just beginning to reap the harvest of computerized innovations that could revolutionize production processes during the 1980s.

Until recently, the rationale for robots was that they were useful in heavy, hot, hazardous and even boring environments. In addition to this ability to remove people from an unhealthy and/or even dangerous environment, robots are a key engine of change in the manufacturing process. Robots, particularly with the addition of computer type circuitry, are the initial entry into flexible automation.

American corporations have been behind the Japanese in recognizing the potential of computers and robots for reducing production costs and increasing the flexibility and versatility of factory operations. While the pentration of robots and computers into

Table 1: Machine Tools in Use*

		% of Total Machines in Use	Under 10 Years	10-20 Years	Over 20 Years	% Numerical Controlled
I.	United States		31.0%	35.0%	34.0%	2.0%
	Transportation Equip.	13.7%	23.8	33.0	43.2	2.1
	1. Motor Vehicles	6.7	23.8	31.4	44.8	0.6
	2. Aircraft & Parts	5.3				
	Non-Electrical Machinery	36.5	32.8	35.1	32.1	3.1
	Electrical Machinery	12.9	33.0	41.7	25.3	1.4
	Fabricated Metal	24.0	27.4	35.2	37.4	0.9
	Precision Instrument	5.0	38.0	36.8	25.1	1.9
II.	West Germany		37.0	37.0	26.0	NA
III.	United Kingdom		39.0	37.0	24.0	NA
IV.	Japan		61.0	21.0	18.0	NA
V.	France		37.0	33.0	30.0	NA
VI.	Italy		42.0	30.0	28.0	NA
VII.	Canada		47.0	35.0	18.0	NA

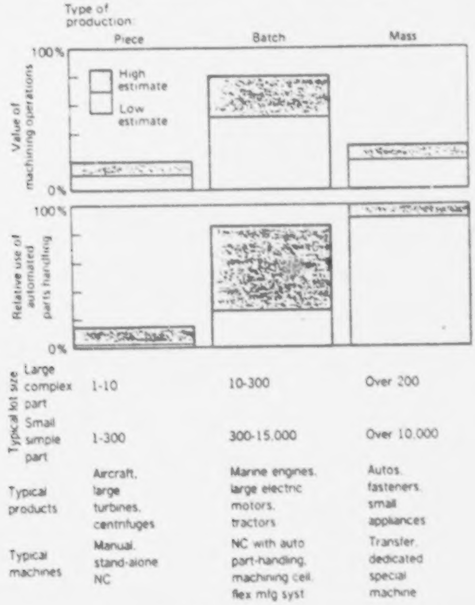
Source: American Machinist: 12th American Machinery Inventory of Metal Working Equipment 1976-78; Verein Deutscher Werkzeugmaschinenfabrik e.V.; NMTBA Statistical Handtools.

*Data based on 1976-78, except for Japan, France and Italy where the data is based on a 1973-75 survey.

the manufacturing world will be concentrated initially into those areas which will result in reduced manufacturing costs primarily through direct labor savings and enhanced quality, the ultimate evolution will probably be toward encompassing that technology as part of a flexible manufacturing systems approach to production. A recent Machine Tool Task Force study highlighted the characteristics of manufacturing (Figure 1) and advocated the development of flexible manufacturing systems to handle production at more economical costs and at an increased rate of productivity.

Characteristics of manufacturing

Figure 1



Source: Machine Tool Task Force on Machine Tool Technology

Table 2: Time Losses in Manufacturing

	Low Volume	Mid-Volume	High Volume
Productive Cutting	6%	8%	22%
Cutting Conditions	2	4	--
Set-up/Loading/Gauging	12	7	14
Tool Change	--	7	7
Idle Time	2	--	--
Incomplete Second and Third Shifts	44	40	--
Holidays and Vacations or Plant Shutdown	34	28	27
Equipment Failure	--	6	7
Inadequate Storage	--	--	7
Work Standard Allowance and Miscellaneous	--	--	16

Source: Machine Tool Task Force on Machine Tool Technology

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The decade of the 1980s will see the need to modernize the U.S. manufacturing base at a time when the change in demographics will result in a sharp decline in the number of workers available for blue collar jobs as well as an overall drop in the number of people entering the work force as a whole. U.S. industry will have to quicken its pace of automation if it is to remain competitive, and only through the widespread use of computers and robots in the manufacturing sector will the automated factory eventually become a reality.

AN ANALYSIS OF ROBOT USE

What Exactly Is a Robot?

Disagreement exists among both foreign and American manufacturers over the appropriate definition of an industrial robot:

- The most widely quoted definition has been published by the Robot Institute of America (RIA), a trade association of trade manufacturers and users. The RIA defines a robot as "...a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable motions for the performance of a variety of tasks."
- The Japanese Industrial Robot Associates (JIRA) specified four levels of robots:
    1. Manual manipulators that perform fixed or preset sequences.
    2. Teaching playback robots that repeat fixed instructions after being taught a work procedure.
    3. N.C. robots executing operations on the basis of numerically coded information.
    4. Intelligence robots that perform various functions through its sensing and recognizing capabilities.

While many other definitions abound, the key difference is that by commonly accepted American standards, a robot should be both programmable and versatile. Hence, the RIA would not include manual manipulators, so that Japanese and U.S. robot population statistics are not precisely comparable. Definitional differences aside, Japan leads all other countries in its acceptance, use and government support of robots. Their industry lead is substantial, particularly when viewed in relationship to the relative size of their GNP.

Table 3: Geographic Distribution of Robots

	As Reported	Using RIA Definition	% of Total
Japan	47,000	10,000	57%
U.S.		3,255	19
Europe			
West Germany	5,850	850	5
Sweden		600	3
Italy		500	3
Poland	720	360	2
Norway		200	1
England		185	1
Finland		130	1
Belgium		20	--
Other		1,400	8
Total		17,500	100

Source: RIA, JIRA, Business Week.

Breakdown of U.S. Market

		Units
Programmable Non-Servo Controlled --General Purpose		1,100
Servo Controlled --Point to Point	1,800	
--Continuous Path	355	2,155
		3,255

Source: JIRA, RIA.

There are basically two classes of robots:

- Non-servo controlled robots in which the tool center point can stop only at the end points of each axis. Many different motions can be programmed in sequence, but only to these end points. There is no provision for acceleration or deceleration.

- Servo controlled robots are far more sophisticated and can generally be programmed to stop at any point within its range of movement. Motion is controlled by oil flowing through servovalves or by D.C. motors, allowing acceleration or deceleration to be achieved.

  Robot control usually takes two forms --point to point and continuous path. A point to point robot can be programmed to stop at predetermined points, but movement is not controlled between these points. A continuous path robot can follow an irregular path exactly.

Low technology robots can often complete a task as well as the more sophisticated models. The Japanese appear more acutely aware of this and tend to concentrate on implementing existing technology. Above all, the industrial robot must be a practical device to successfully penetrate the manufacturing world. Our discussions with many industrial manufacturers indicates three key characteristics required by users:

1. Flexibility of applications, either in the area of (material) handling or as a processor (painting, welding, etc.).

2. High level of reliability with a minimum of downtime.

3. Ease of teaching, either with on or off line programmability, usually with teach boxes.

Who Would Use
Robots: How and Why

In 1979 the RIA estimated that six industry segments accounted for the bulk of unit robot shipments in the U.S.

Table 4: 1979 Estimated Unit Shipments

	Units	% of Total
Automotive	249	18
Casting/Foundry	298	21
Heavy Manufacturing	138	10
Light Manufacturing	513	37
Electrical/Electronic	156	11
Aerospace	13	1
Other	33	2
Total	1,400	100

Source: RIA.

As the majority of robots installed in the U.S. today are low or medium technology devices, the analysis of user purchases of robots by value would probably yield a different hierarchy of industry segments, with the automotive industry clearly in front. Our end use market by industry sector appears to be developing along the lines of the Japanese industry (Table 6).

Table 5: Japanese Market
Production Share of Industrial Robots, by Type

	% Units	% Value
Manipulators and Sequential Robots	89%	70%
Teaching Playback Robots	5	17
N.C. Robots	1	4
Intelligent Robots	5	9

Source: J.I.R.A.

Table 6: Value of 1979 Robot Shipments to Users in Japan

Automobile Industry	38.4%
Electrical Machinery	17.5
Plastic Molding	10.8
Metal Products	8.1
Precision Machining & Metal Working	6.0
Iron & Steel	4.2
Other	15.0
Total	100.0

Source: J.I.R.A.

Whether or not the auto industry was the dominant purchaser of robots in the U.S. in the .970s is a moot point; it clearly will be the driving force for the industry in the 1980s. It's no longer a secret that General Motors has projected an installed base of robots in its facilities as high as 14,000 by 1990.

Table 7: Possible GM Robot Base (Cumulative)

	1978	1979	1980	1984	1986	1988	1990
Cumulative	160	230	302	3,500	6,500	10,000	14,000

Source: GM.

As the robotics market is expected to be dominated by the automotive and other heavy manufacturing segments, at least during the first half of the 1980s, the principal applications are unlikely to vary significantly from the current uses over the near-term:

- Spot welding, which we estimate to account for 35-40% of total robot industry sales.
- Material handling, including machine loading and unloading.
- Die casting, investment casting, stamping, forging and press loading.
- Paint spraying and finishing.
- Palletizing.
- Assembly.

Toward the middle of the 1980s, arc welding systems should begin to grow rapidly and become the most important welding sector as demand for spot welders plateaus. During the latter part of the decade, it is likely for arc welders, machine loading and unloading and assembly robots to be the primary areas of growth, with assembly alone perhaps representing 35-40% of the total and perhaps nearly half of the annual growth.

The traditional rationale as to why industry purchased robots was that they offer a means to increase productivity and free workers from boring and unsafe tasks. A recent Delphi Survey by the Society of Manufacturing Engineers (SME) indicates that there are two key factors as the important crieteria for robot purchases:

1. Reduce manufacturing costs

2. Provide direct labor savings.

Other factors also cited include enhanced product quality, an improved working environment and tying into other forms of computerized automation though the relative importance of these are clearly below the first two mentioned. The median average expected payback period runs between 2-3 years and is not expected to change materially during the first half of the 1980s.

Table 8: Median Average Expected Payback Period

	Now	1985
Automotive	2.7 Years	2.0 Years
Casting/Foundry	3.0	2.5
Heavy Manufacturing	3.0	3.0
Light Manufacturing	2.0	2.0
Electrical/Electronic	2.0	2.0
Aerospace	2.0	2.5

Source: RIA.

While foreign built robots are not a significant factor currently, it is expected that increased exports from Japan by 1983 as well as foreign owned U.S. manufacturing facilities will lead to foreign manufacturers maintaining a significant presence in the market. The SME survey suggested that 20% of the dollar value of robots is likely to be supplied by foreign manufacturers, with cost advantage and overall quality (manufacturing and design) being the key factors that led to a foreign built purchase.

Robot Demand Expected To Be Sensitive To Economic Cycles

It appears quite likely that demand for robots as well as other factory automation equipment will be a cyclical as well as a growth market. Using expected cost reduction and direct labor savings as well as productivity improvement as part of a return on investment analysis suggests that manufacturers will be sensitive to a reduction in business expectations and cash flow which can result from an economic downturn. This has been the case in Japan where industrial robot sales in terms of both unit production and value showed moderate sensitivity to economic conditions in 1971 and 1975 despite the small size of the industry.

It is conceivable for the U.S. robot sector to evolve into a strong cyclical growth market somewhat akin to the minicomputer or semiconductor sector, i.e. strong unit and sales growth with each trough in demand significantly higher (perhaps 30-40%) than the previous trough.

Table 9: Production of Japanese Industrial Robots

	Units (000 Units)	Value (¥ Bill)
1968	0.2	0.4
1969	0.4	1.5
1970	1.7	4.9
1971	1.3	4.3
1972	1.7	6.1
1973	2.5	9.3
1974	4.2	11.4
1975	4.4	11.1
1976	7.2	14.1
1977	8.6	21.6
1978	10.1	27.3
1979	14.5	42.4

Source: JIRA.

AN ANALYSIS OF ROBOT MANUFACTURING

Multisector Industry To Evolve in the 1980s

In 1980, sales of robots by U.S. based companies approached $100 million, up sharply from the estimated $60-65 million in sales in 1979. While a growth of 50% is impressive during a recessionary environment, the robot industry size was still less than 2% of the $4.69 billion machine tool industry with which it often was mistakenly included and an insignificant part (4/1000 of 1%) of U.S. GNP. While robots are commonly assumed to be an extension of the machine tool industry because of its strong ties with manufacturing, we believe that the industry will evolve into its own subset of the flexible automation equipment sector with a multitude of segments much akin to the early development of the minicomputer industry in the 1960s and early 1970s. However, in contrast to the minicomputer industry, it is conceivable for the major participants in robotics to significantly change character by the next decade. We believe it is likely for a significant portion of robot manufacturers to become part of major companies organized to supply systems and subsystems for the factory of the future. A pure robot company might only service a small, specialized segment of the factory automation market.

It is our opinion that the structure of the robotic sector will evolve in a manner similar to the early stage development of the minicomputer industry. Through the mid-1960s, the minicomputer industry was dominated by two major computer manufacturers. Beginning in the second half of the 1960s and into the 1970s, this sector developed a more elaborate structure.

Table 10: Structure of the Minicomputer Industry in 1970

	Buys	Makes	Sells to
Minicomputer Manufacturers	Peripherals Software	Mainframes Peripherals Software Systems	OEM's Independent systems houses End-user
Peripheral Equipment Manufacturers	Minicomputers Software	Peripherals (includes terminals and secondary memories) Minicomputers	Minicomputer manufacturer OEM Independent Systems Manufacturer End-user
Original Equipment Manufacturers	Minicomputers Peripherals Software Engineering	Peripherals Software Systems Minicomputers	End-user
Programming	–	Software	OEM End-user
Independent Systems	Minicomputers Peripherals	Systems Software	OEM End-user

The interfaces depicted by this structure can essentially be split into four subsegments:

1. The end users who could. . .

2. purchase a system from the original equipment supplier directly, or. . .

3. sometimes go to a group of independent consultants who help the purchaser put together systems and subsystems, or. . .

4. sometimes turn to a company that has developed a turnkey product using OEM supplier equipment as the heart of the system.

As users became more sophisticated, they assumed greater responsibility for the integration of the system. A service segment began to evolve about a decade later as the indicated base of the product grew.

The robot industry appears to be developing along the same lines. Currently, two manufacturers, Unimation (subsidiary of Condec) and Cincinnati Milacron, dominate the industry with an estimated 70% of the market. These companies are four to five times larger than the nearest competitor (Table 11).

Table 11: Estimated 1980 U.S. Robot Sales by Manufacturer

	Sales Millions
Unimation (Condec)	$ 40.0
Cincinnati Milacron	30.0
DeVilbiss (Champion Spark Plug)	9.0
ASEA (U.S. Operation)	7.5
PRAB	6.0
AutoPlace (Copperweld)	4.5
Nordson	0.7
Mobot	0.7
Automatix	0.4
Other	1.2
Total	100.0

Source: PWMH.

Purchasers during the early marketing stages worked with the robot supplier in order to integrate robots into the manufacturing process and occasionally outside consultants were used because of the lack of support available for the process.

Over the past several years, U.S. manufacturers have shown increasing interest in the concept of families of parts for greater manufacturing efficiency. This has heightened the interest of U.S. companies in flexible manufacturing systems and manufacturing cells with the primary goal of generating a high level of production of a wide range of family components with the flexibility to change, a capability previously available only with a sharp reduction of output. This change in the manufacturing concept has refocused the efforts of robot manufacturers toward the growing areas of applications and systems. Moreover, new companies such as Automatix, Inc. and Robogate Systems Inc., were founded on the concept of turnkey installations integrating robots into flexible manufacturing systems.

The likely evolution of these developments can probably be illustrated by the responses of U.S. manufacturers to the 1981 SME Delphi Forecast for Robotics (Table 12). In essence, the purchasers of robots will continue to make use of independent consultants, but also will turn more and more to turnkey system suppliers during the 1980s.

Table 12: Users Will Seek More Help for Robot Integration (Median Estimate)

	1980	1985	1990
% of Robots Purchased by Users with Assistance of Outside Independent Consultants Doing Systems Engineering	10%	15%	15%
% of Robots Procured as a Turnkey Package with One-Source Layout, Robot Supply and Installation	20	25	30
Purchaser Procures on Individual Basis; Purchaser Assumes Responsibility for Layout and Integration with Installation Done by Equipment Manufacturer	80	70	70

Source: 1981 SME Delphi Forecast --Median Results.

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Longer-Term Trends: Automation Companies Will Likely be Large

While robots are often used in an initial isolated application (primarily to gain experience) the evidence is clear that the robot is viewed as a piece of equipment to be integrated into the production process. Moreover, the U.S. production base is in dire need of modernization and, most important, the mid-1980s demographic shift will lead to a drop in the entry level work force at a time when the average skilled machinist in this country is currently estimated to be about 56 years old. These fundamentals suggest that U.S. manufacturers will have to adjust their methods and philosophy of production, emphasizing the substitution of capital for labor or, in one word --automation.

The evolution of factory automation outside the U.S. has an interesting characteristic. Most of the companies in the forefront of the technology are part of the organization that makes much of the equipment used. What emerges is that the knowledge of the factory environment is the key factor to the successful implementation of automation. In Japan, for example, Toyota was originally a subsidiary of a machine tool company (Toyoda) and its machine tool technology cannot be sold externally without the car company's approval. Nissan has a machine tool company as does Hitachi and Komatsu, the sixth largest producer of transfer lines in Japan.

A similar phenomenon is developing around the world with respect to the implementation of Robots, i.e. many of the companies introducing robots into the manufacturing process produce a version for internal consumption. Besides many Japanese concerns, the list would also include companies such as Volkswagon, Renault and Fiat.

Alternatively, U.S. manufacturing companies rarely produce equipment for their own use. However, as automation techniques begin to take hold, the phonomenon has begun to change. In robots, for example, companies like General Electric, Texas Instruments and IBM all produce robots for internal use and General Motors recently announced its own paint spraying robot. Further, strategic planning within many corporations has led to the identification of the field of automation as both a strategic internal operation requirement and a future business opportunity. This has led to significant acquisitions and internal studies as to how to best service this cyclical growth phenomena (Table 13).

Table 13: Strategic Purchases by Large Companies in the Field of Automation

	Bought
Energy Related Companies	
Exxon Schlumberger	Reliance Electric Fairchild Manufacturing Data Systems Inc.
General Electric	Calma Intersil License DEA Allegro Robot
Transportation Related Companies	
Eaton	Cutler Hammer Kenway
Bendix	Warner & Swasey
Other Companies with Automation Related Divisions	
TRW Gould Square D Litton	
Automation Approach Under Study	
IBM Texas Instruments Digital Equipment Westinghouse Emerson Electric	

Source: PWMH.

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The logical evolution of the factory of the future company is one which can put together the sophisticated systems largely involving computer technologies, electronics and software, controllers and, of course, robots. The requirement for the various technical disciplines, the high development costs and financial and marketing skills suggest that these companies will tend to be quite large in nature, with suppliers of industrial pieces of equipment occupying a small niche in the broad spectrum market for the automated factory.

Robot Production: Generalists With A Niche for Specialists

The potential widespread use of robots suggests that the industry will continue to segment in various ways:

- Work envelope and load capacity applications have often been the determinant of market segmentation by lift capacity:
  1. Extremely heavyweight applications (lift capability in excess of 350 lbs.)
  2. Heavy applications, including spot welding resulting in lift capacity between 50 and 350 lbs.
  3. Medium to low weight applications requiring lift capacity of less than 50 lbs.
- Small parts, pick and place and assembly requirements led to the development of the market for robots with lift capacity of less than five pounds. The driving force for market development was the realization that upwards of 90% of the parts of the average automobile weighed less than three pounds.
- Segmentation by process applications, including painting, spraying and coating and arc welding.

An analysis of these market segments suggested that a family of general purpose robots with a choice of drive mechanism, lift capacity and wrist configuration could be produced, with the intelligence of the robot (electronics and software) used to tailor the general purpose robot for a specific application. While the major robot producers have adopted this approach, a small market nich has also developed for a dedicated system, particularly in paint spraying, primarily because of the intricacies of coating technology. We believe it is likely for this generalist approach to pervade in the industry, with some specialized niches developing because of unique process technologies.

R&D: A Crucial Investment

For robots to be useful across a wider breadth of markets in the future, they must be able to adjust automatically to alternative production set-ups and have the capability of recognizing reorienting and manipulating disordered parts. For many assembly and installation procedures, this adaptive ability would be essential.

The key to the wide market expansion, we believe, lies in the breakthrough in at least two areas of technology:

- Sensory capabilities, including:
  1. Force with application in fitting operations.
  2. Tactile with application in both positioning and orienting.
  3. Vision with application in positioning, inspection and monitoring.

- The ability of the robot to interface with large, computer controlled manufacturing systems. This includes the ability to create a task description without the necessity of using a robot's actual motion. The development of off-line programing would also ease the actual programing task.

Further, the key to better robots lies in vastly improved electronics and software, enhancement of existing software and incorporation of advances in other areas, such as:

- Material: Robots in the future are likely to be built out of various composites and/or plastics rather than metal.
- Spread processes such as coating techniques.
- Mechanisms and material handling.

This suggests that robots have all the characteristics of a high technology industry:

1. High levels of R&D spending are a must, with 7-10% of sales, or more, likely. (Note: Similar to the semiconductor industry.)
2. The vast number of technologies involved suggest that joint ventures are likely to occur for advancing the state of the art in robots:
   - Unimation's PUMA robot was developed in a joint venture between GM and Unimation. Development of the product ended the relationship.
   - Cybotech has been formed as a joint venture corporation by Renault and Ransburg, hopefully to develop a robot by bringing the expertise of two companies together.
3. Significant R&D will be done by academia with support help from companies. This is particularly true in sensors and some vision work is currently being done by RPI, Purdue, UCLA, Florida State (Gainesville), Stanford, University of Rhode Island, etc.

R&D ability is fast becoming a barrier to entry in the robot field. Further, it is likely for proprietary technology to be much more important than patent protection, similar to the major technological fields dominated by software and electronics.

Learning Curve Pricing Key to Industry Growth

The heavy emphasis on computers, electronics and software as the key method of adapting general purpose robots for specific application suggests that the pricing of robots will follow the characteristics of high technology industries. Currently, we estimate that around 30% of the cost of a robot is the electronics and software, with even a higher percentage for the more sophisticated models. Hence, we believe that the learning (experience) curve is very important to robotics, and prices should fall as volume increases. For example, one of the major manufacturers introduced its robot line four years ago. Despite the widely inflationary times of the past few years, selling prices have remained essentially unchanged, implying an estimated 30% price reduction in real terms --directly related to the sharp volume increases.

While the base price of robots is likely to decline, the average price per unit is likely to increase over the next five years. This reflects that robots will probably be equipped with more extensive accessories such as sensors and vision. Assuming technological advancement and learning curve pricing, we believe that the robot industry during the 1980s could achieve a revenue growth upwards of 35% (cyclically), with industry revenues estimated at $500-600 million by 1985 and approaching $2 billion by 1990.

Table 14: Rapid Robot Industry Growth Projected

	Sales Millions	Units
1981	$ 150	2,100
1985	500-600	7,000- 8,000
1990	2,000	30,000-40,000

Source: PWMH.

As in most high technology industries, the cost of being wrong in product and/or market decisions is high and could easily be catastrophic for smaller entrepreneurial concerns.

One potential future market development is the growth of the robot leasing business. As in the computer business, small companies may never have adequate capability to implement robots efficiently. Leasing robots, along with full support from suppliers, could make sense for smaller companies with limited capital and no robot-wise employees, making the latest technology readily available.

ROBOT INTRODUCTION A SIGNIFICANT IMPACT ON MANUFACTURING OPERATIONS

There is no doubt that robots will revolutionize the workplace. Even if no further technological advancements were made in fields such as sensory percention, robots would still have a place in the manufacturing process. However, it is impossible to ignore the awkward period of realignment that must precede the robotics revolution. It is clear that technology is far more sophisticated compared to the understanding of the social system of the factory.

Robots are threatening to the existing work force. Recent estimates have suggested that upwards of twenty million industrial jobs around the world could be replaced by robots. This includes four million assembly workers, two million machinists, one million painters, two million welders and flame cutters and six million machine operators. Retraining is believed to be the major social problem created by rapid robotization, not unemployment.

In both the U.S. and Sweden, for example, many unions have come to accept robots as a method of easing the most burdensome manufacturing tasks and increasing productivity, both viewed as a route to a higher standard of living. Swedish unions have actually classified certain dangerous or monotonous jobs as unfit for humans and demanded that they be carried out by robots. The UAW has been quoted in publications as stating that higher wages and productivity go hand in hand and technology, automation and new methodology are a major way to increase productivity.

The method of robot introduction into a manufacturing organization tends to follow the pattern of selling an initial unit to a company. The sale by the manufacturer has to include:

- Extensive customer support, including back-up support and technical services, simple repairs and parts replacement.

- Comprehensive training programs and customer education, as potential users often do not have the technical background or expertise to make a robot work on the plant floor.

The first installations tend to be most important, for they are the ones watched most carefully by both management and labor. As companies become more comfortable in using robots, multiple orders follow, but the need for continuing manufacturers' support remains. In the future, robot producers will have to face the problem of support networks that extend throughout the world and offer a variety of services, including education.

Within the manufacturing corporation, the jobs created by widespread use of robots and unmanned manufacturing --programmers, technicians, engineers --for the most part require a high degree of technical training. The jobs which robots eliminate, e.g. assembly workers, painters and machine operators, are frequently of a lower skill or, if even skilled, require little technical knowledge. Massive training programs will be needed to prevent the creation of an oversupply of workers whose skills have become obsolete and a simultaneous shortage of engineers and technicians. It appears that the manufacturing industry has recognized the problems by the responses to the SME Robotics Delphi Poll (Table 15).

Table 15: Sources of Future Robotic Technical Personnel

Updated In-House Manufacturing Engineering Personnel	50%
Hiring of Experienced Personnel from Manufacturer	20
Hiring of Experienced Personnel from Robot Vendor	10
Graduating College Student	15

Source: 1981 SME Delphi Poll.

To date, however, only the barest beginnings of such programs are in place. We also have recently seen the development of an academic robotics curriculum to help meet the demand for robot technicians. Macomb County Community College in Warren, Michigan has just introduced such a program and the State of South Carolina is subsidizing academic training programs at locations near the new Cincinnati Milacron robot plant.

While we believe the critical issues of manufacturing techniques and labor displacement can be handled in the short-term, we are becoming more concerned that the magnitude of the problem could be serious during the second half of the 1980s. Technological advances enhance the capability, economic viability and availability of assembly and inspection robot systems:

. The design of products that are compatible with robot handling will increase in importance. One implication is that the robot specialist will have to be involved in the product design phase.

. It is estimated that assembly workers constitute upwards of 15% of the U.S. manufacturing work force, and inspection workers probably 5-10%. These are two areas where advanced robotics could be applied with astonishing impact.

CAPITAL: KEY TO SUCCESS OF BOTH PRODUCERS AND USERS

The need to finance a business in an industry capable of growing 35% annually and requiring significant levels of R&D and an extensive support network suggests that profitability and availability of capital is vital. Fortunately, it appears that the members of the robot industry have been able to tap the capital market as needed. There is no doubt that all the favorable publicity the robot sector has received, including being on the covers of both Time and Business Week in 1980, has helped contribute to the exceptionally favorable opinion held by the investment community as to the prospects for robotics.

It is our view that the government would probably not have to get intimately involved in the financial requirements of the robotics industry. A free market approach should allow this sector to attract the necessary capital required because of the well-above average growth prospects. This does not preclude the necessity of general policy incentives required by American businesses. We believe that tax relief, especially higher depreciation write-offs, are the kinds of programs which would benefit robot producers as well as manufacturers.

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Government programs which could be useful in the future would be in the area such as aiding R&D expenditures through either tax credits or government funds being made available for basic research.

We believe government aid to the users would be more beneficial to robot manufacturers. This could take the form of:

- Helping companies afford the introduction of robotics into their production process. We believe this aid could become crucial for smaller companies.
- Establishing some sort of showcase, perhaps a national demonstration program, to provide inspirational leadership and develop a cogent policy for manufacturing techniques.

We believe that manufacturers' ability to afford robots and other aspects of factory automation is ultimately related to their cash flow. A stable period of economic growth, reasonable levels of interest rates and controlled inflation as well as government tax policies providing investment incentives would typify the ideal environment for companies in general to increase their investment in automated equipment.

However, it's important to note that the introduction of robots into the manufacturing process essentially breaks the shackles as to how things are done. This implies an important degree of risk for companies to implement robotic programs, a risk taken currently by the larger companies in this country.

It appears that government incentives could be exceptionally useful in helping smaller companies absorb the technological risk of introducing automated equipment. The Japanese government, through the Ministry of Trade and Industry (MITI), has adopted programs addressing this issue in line with the decision that robot production is a major strategic industry for Japan's future:

- MITI has permitted manufacturers who install robots to depreciate an additional 12½% of the purchase price in the first year.
- MITI has arranged for direct government, low interest loans to small and medium scale manufacturers to encourage various type of robot installations.
- MITI has helped encourage the founding of a robot leasing company --Japan Robot Lease. The objective is to support robot installations by small and medium scale manufacturers.

We believe it would be advantageous for U.S. policy to consider following the lead of the Japanese. We also believe that the U.S. government could consider programs to help foster the spread of automated techniques throughout industry. Heretofore, the Japanese have led the way with the Japanese Automated Factory Project sponsored by the Agency of Industrial Science and Technology of MITI. The project, initiated in 1977, aims to help take existing technological advances into the marketplace, with the acknowledged long-term goal of unmanned manufacturing.

LONG TERM: A REPLAY OF THE AGRICULTURAL SECTOR

Today, 3.8% of the U.S. work force is in agriculture, a major change from yesteryear, when it was the dominant employment sector. This 3.8% produces enough food to feed this country and makes the U.S. the leading exporter of food. The decline of population in the agricultural sector occurred with the substitution of capital for labor. There are many people who believe that, through automation, the percentage of the work force in manufacturing will decline significantly from the current 28.6%. While we do not necessarily believe the extreme number of 1-3% in the next century, there is no doubt that the U.S. work force employed in manufacturing as we know it today will markedly decline over the next 25 years. Through technology such as electronics, software, and systems architecture including robots, eventually the automated factory will begin to be a reality.

July 31, 1981 Eli S. Lustgarten (312) 580-8213

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